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Title: Mixing Experiments at Los Alamos

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Mixing Experiments at Los Alamos

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September 9, 2013

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P-23 Physics Extreme Fluids Team

We are focusing on mixing and turbulence modeling, experiments, and simulations

HST **Horizontal Shock Tube:**

- Richtmyer-Meshkov Experiments on gas curtain
- Retrofit of HST for multiphase flow experiments

VST **Vertical Shock Tube:**

- Single-Interface RM

TMT **Turbulent Mixing Tunnel:**

- Subsonic, variable-density mixing

We are using a variable-density turbulence RANS model that was developed at Los Alamos*

$$\frac{\partial \bar\rho K}{\partial t} + \frac{\partial \bar\rho K \tilde u_n}{\partial x_n} = \underbrace{a_n \frac{\partial \bar p}{\partial x_n} - R_{in}\frac{\partial \tilde u_i}{\partial x_n}}_{\text{Production (exact)}} + \underbrace{\frac{\partial}{\partial x_n}\left(\bar\rho \nu_t \frac{\partial K}{\partial x_n}\right)}_{\text{Diffusion}} - \underbrace{\bar\rho \frac{K^{3/2}}{S}}_{\text{Dissipation}}$$

$$\frac{\partial \bar\rho S}{\partial t} + \frac{\partial \bar\rho S\tilde u_n}{\partial x_n} = \frac{S}{K}\left[\left(\frac{3}{2} - C_4\right)a_n\frac{\partial\bar p}{\partial x_n} - \left(\frac{3}{2} - C_1\right)R_{nm}\frac{\partial \tilde u_n}{\partial x_m}\right]$$

$$- C_3\bar\rho S\frac{\partial\tilde u_n}{\partial x_n} + \frac{\partial}{\partial x_n}\left(\frac{\bar\rho\nu_t}{\sigma_\varepsilon}\frac{\partial S}{\partial x_n}\right) - \left(\frac{3}{2} - C_2\right)\bar\rho\sqrt{K}$$

$$\frac{\partial\bar\rho a_i}{\partial t} + \frac{\partial\bar\rho a_i\tilde u_n}{\partial x_n} = b\frac{\partial\bar p}{\partial x_i} - \frac{R_{in}}{\bar\rho}\frac{\partial\bar\rho}{\partial x_n} - \bar\rho a_n\frac{\partial(\tilde u_n - a_i)}{\partial x_n} + \bar\rho\frac{\partial a_i a_n}{\partial x_n}$$

$$- \frac{C_{a1}\bar\rho a_i\sqrt{K}}{S} - \bar\rho a_n\frac{\partial(\tilde u_i - a_i)}{\partial x_n}$$

K – Turbulent kinetic energy/unit mass

S – Turbulent length scale

a – mass flux velocity

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* D. Besnard, F, Harlow, R. Rauenzahn, C. Zamach, 1992. "Turbulence Transport Equations for Variable-Density Turbulence and Their Relationship to Two-Field Models, Los Alamos Report LA-12303-MS.

In the 2011 version of the BHR turbulence model, *b* is evolved. We are adding an additional length scale now

$$\frac{\partial \bar{\rho} b}{\partial t} + \frac{\partial \bar{\rho} b \tilde{u}_n}{\partial x_n} = \underbrace{2\bar{\rho} a_n \frac{\partial b}{\partial x_n} - 2(b+1) a_n \frac{\partial \bar{\rho}}{\partial x_n}}_{\text{Production (exact)}} + \underbrace{\bar{\rho}^2 \frac{\partial}{\partial x_n}\left(\frac{\nu_t}{\bar{\rho}\sigma_b}\frac{\partial b}{\partial x_n}\right)}_{\text{Diffusion}} - \underbrace{\bar{\rho}\frac{C_b\sqrt{K}}{S} b}_{\text{Dissipation}}$$

$$b = -\overline{\rho'\left(\frac{1}{\rho'}\right)}$$ Density–specific volume correlation

$$K = \frac{R_{nn}}{2\bar{\rho}}$$ Turbulent kinetic energy

$$R_{ij} = \overline{\rho u_i'' u_j''} = \boxed{\bar{\rho}\,\overline{u_i' u_j'} - \bar{\rho} a_i a_j + \overline{\rho' u_i' u_j'}}$$ Reynolds stress tensor

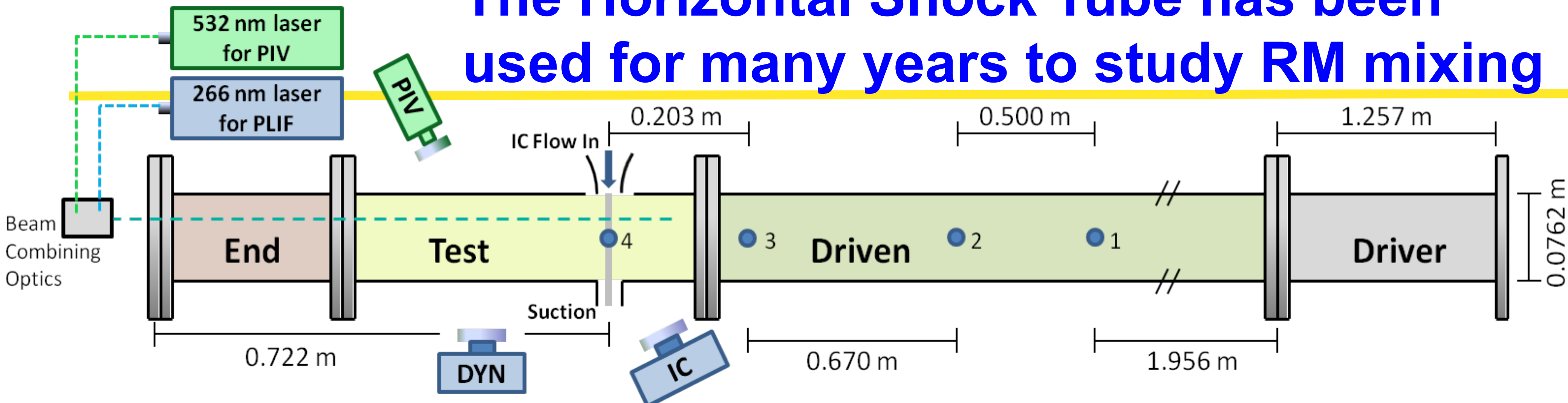
$$a_i = -\overline{u_i''} = \boxed{\frac{\overline{\rho' u'}}{\bar{\rho}}}$$ Mass flux velocity

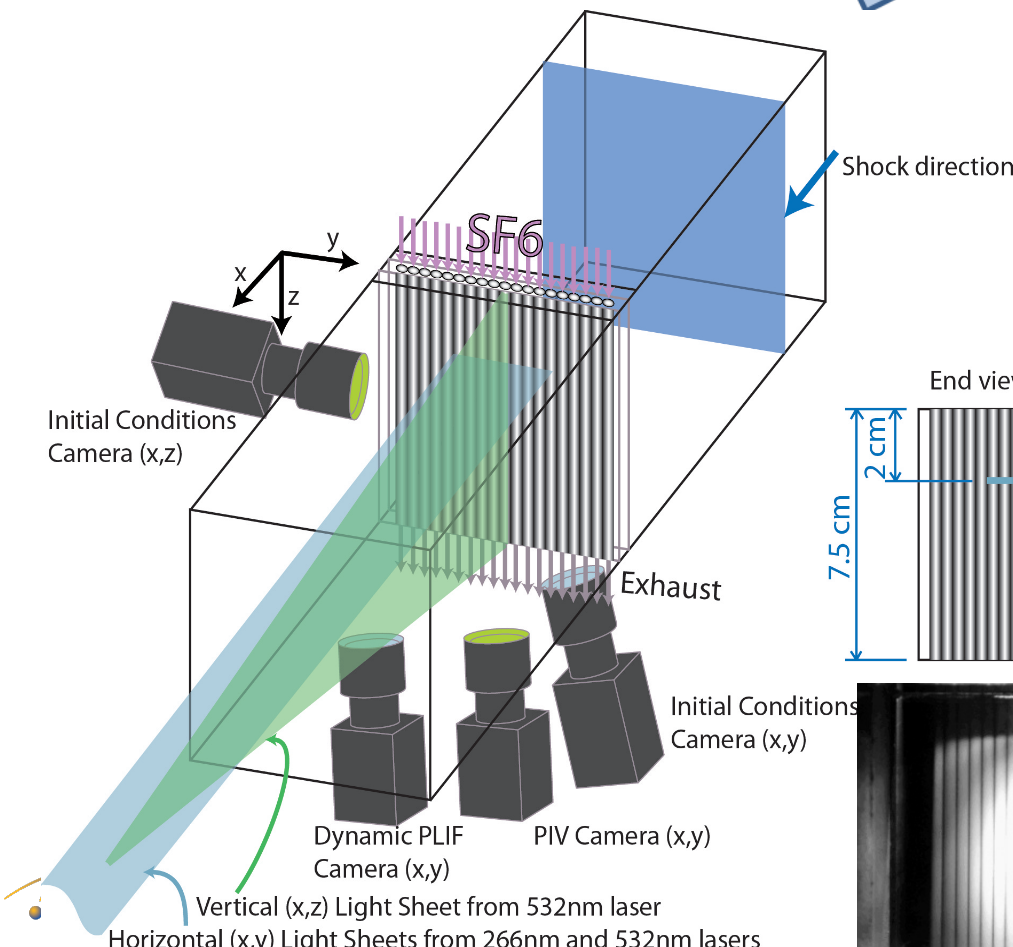
$$\nu_t = .09 S\sqrt{K}$$ Eddy viscosity

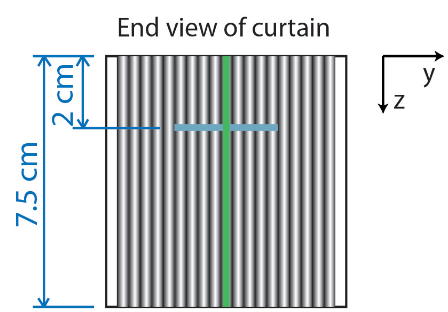
- Latest version of model: Schwarzkopf, Livescu, Gore, Rauenzahn, Ristorcelli, “Application of a second-moment closure model to mixing processes involving multicomponent miscible fluids,” J. of Turbulence, 12(29), 2011.

HST

The Horizontal Shock Tube has been used for many years to study RM mixing







Our final gas curtain study focused on Mach effects:

M = 1.21, 1.36, 1.50

Orlicz *et al.*, to appear, Phys. Fluids 2013

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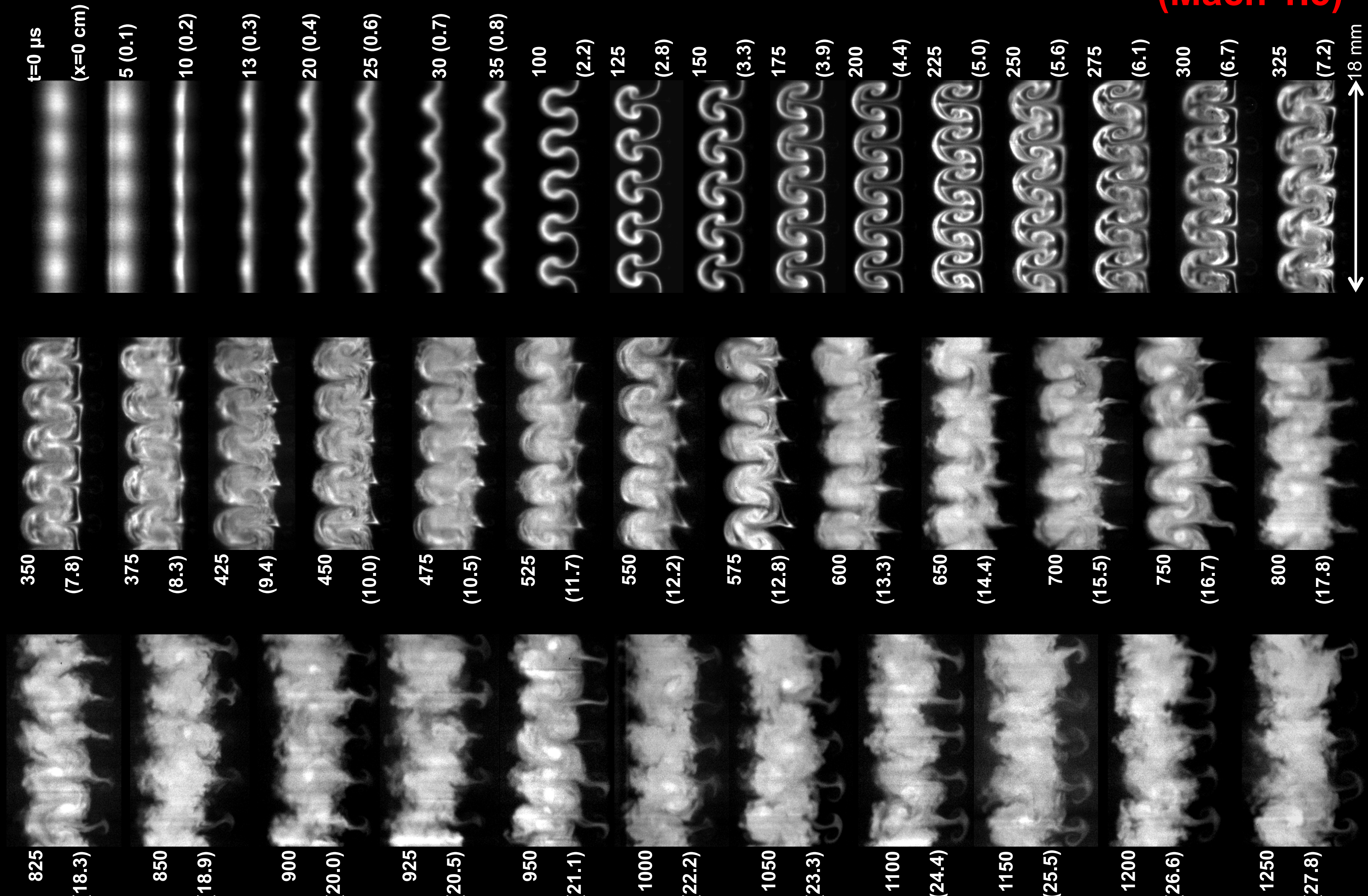
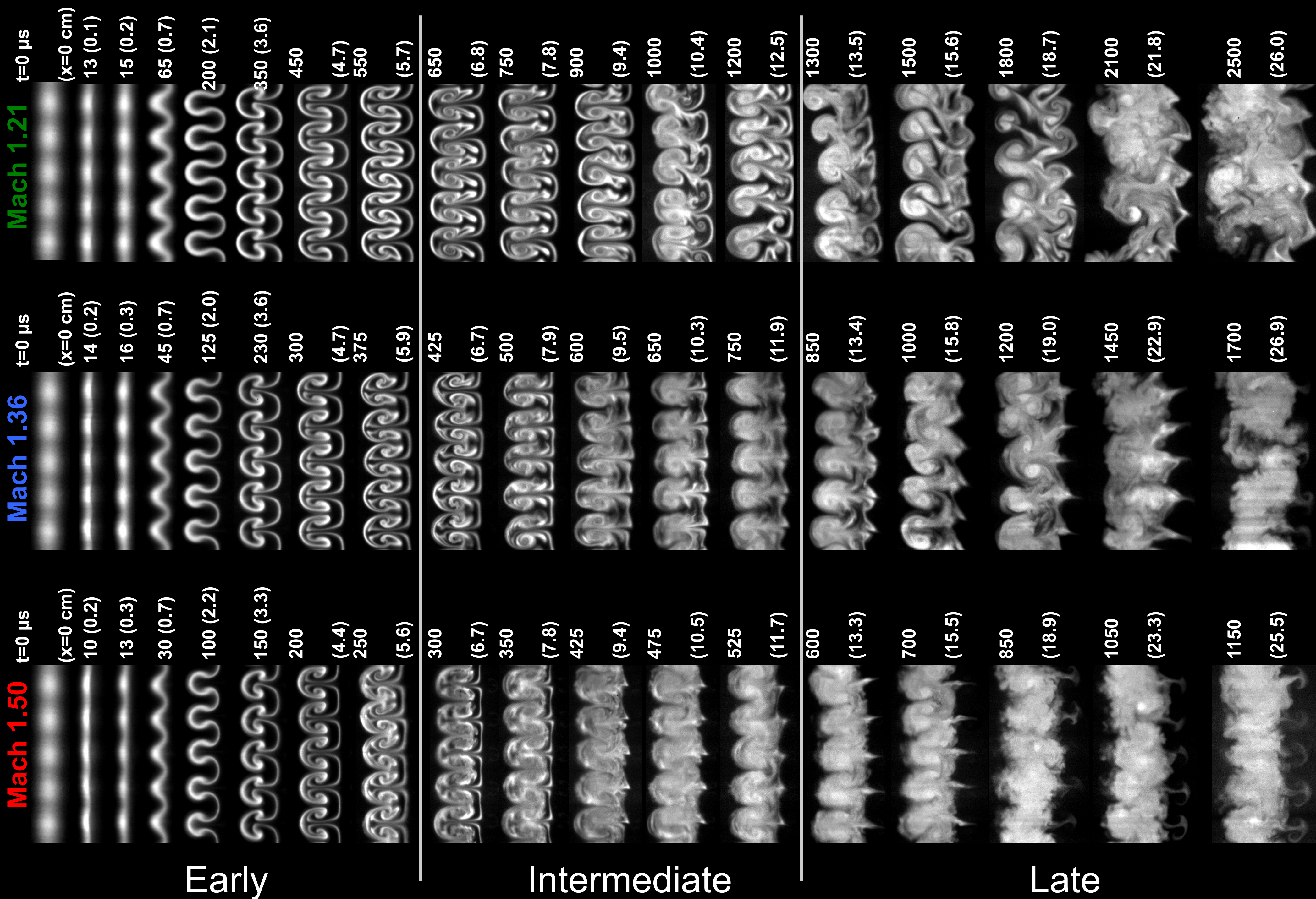
We can observe large and small-scale mixing with high spatial and temporal resolution to distinguish different flow conditions

(Mach 1.5)

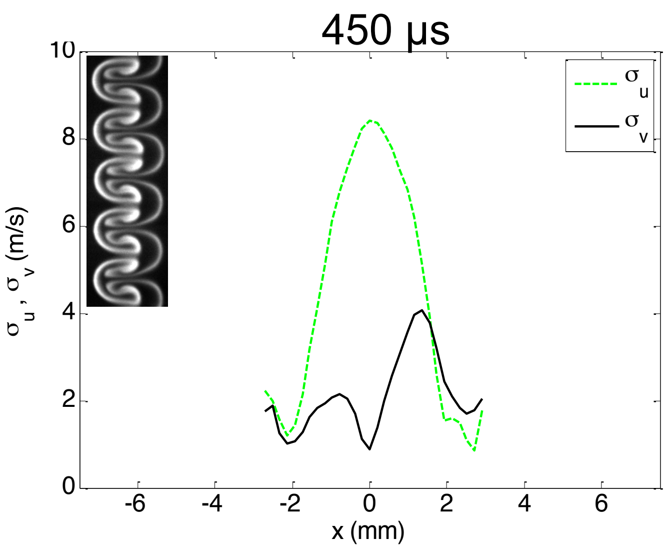


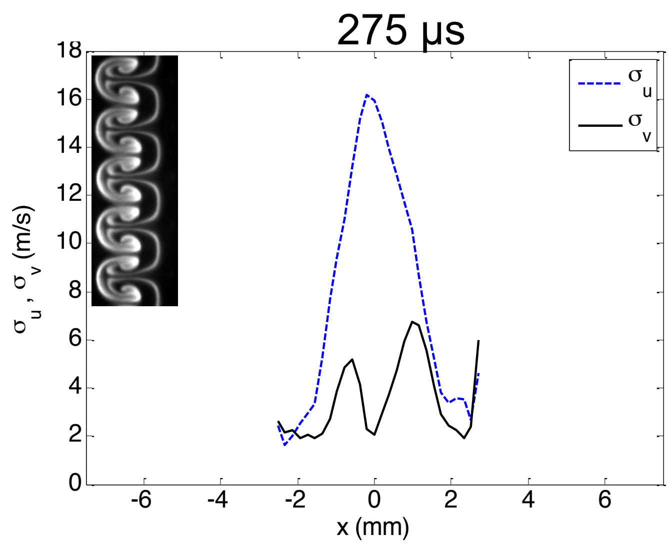
Early time development is qualitatively similar, but mixing differences are visible at later times. Can we quantify?

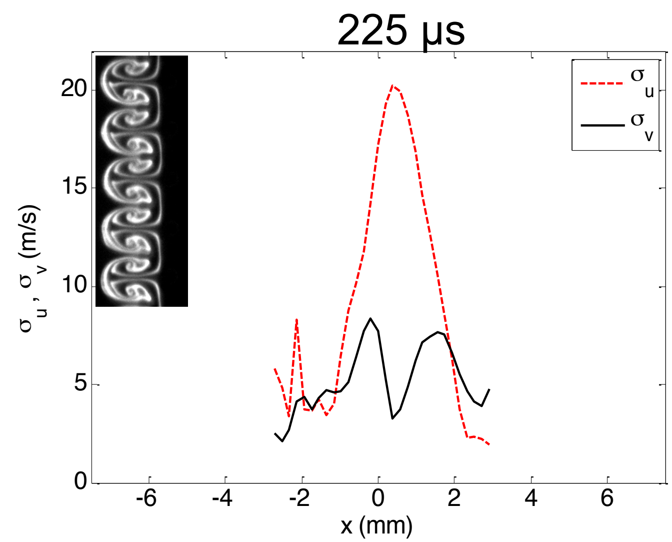


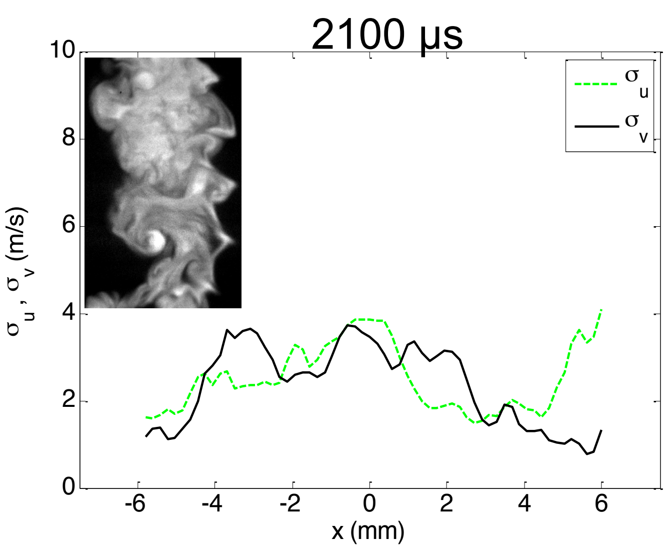
In all *Ma*, the RMS velocity fluctuations indicate more isotropic mixing at late times

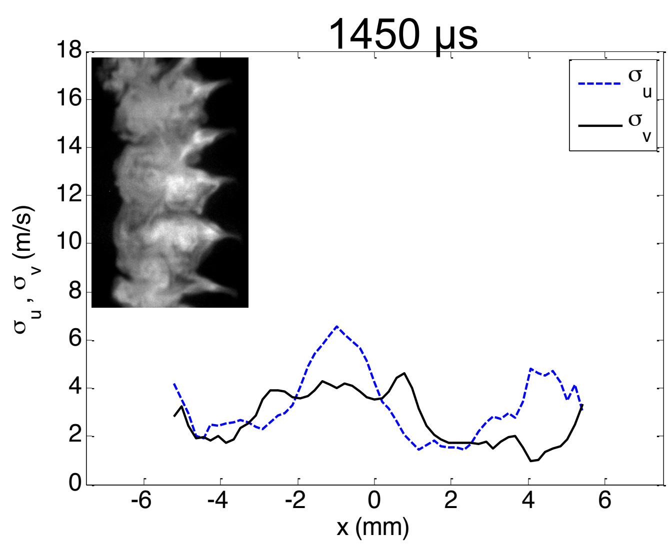
Mach 1.21 | Mach 1.36 | Mach 1.50

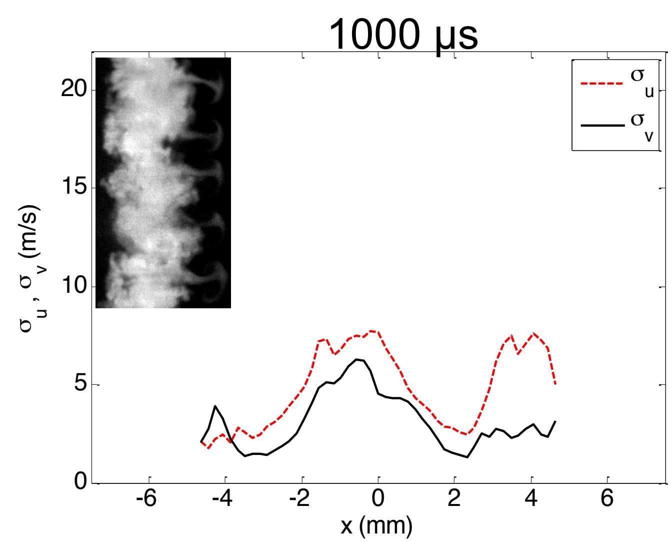








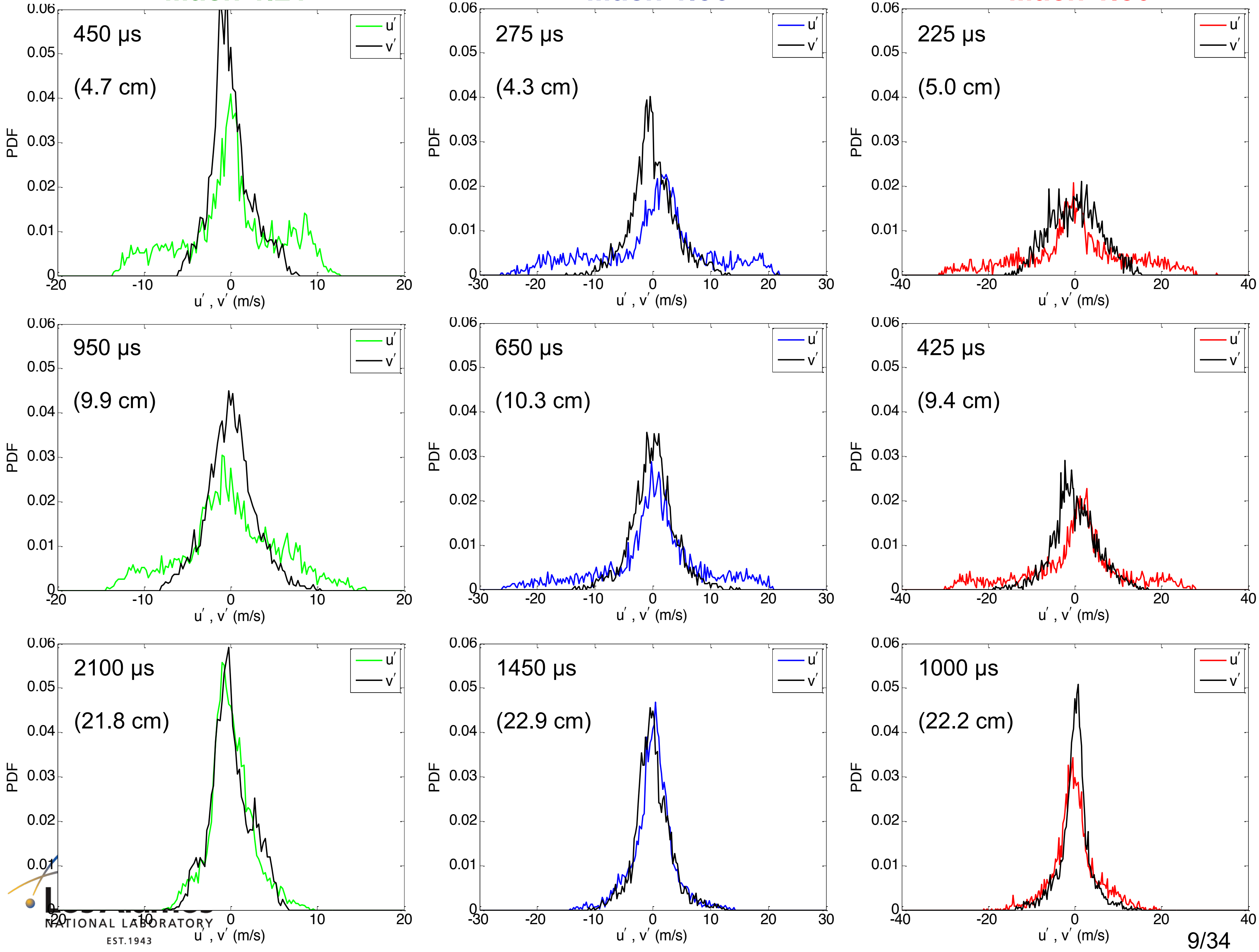




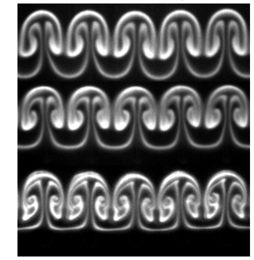
HST

PDFs of velocity fluctuations also indicate more uniform mixing at late times, with *Ma* differences

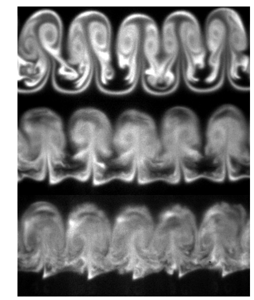
Mach 1.21 | Mach 1.36 | Mach 1.50



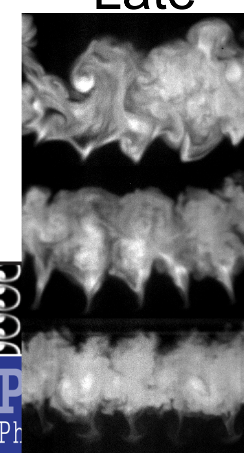
Early



Intermediate



Late



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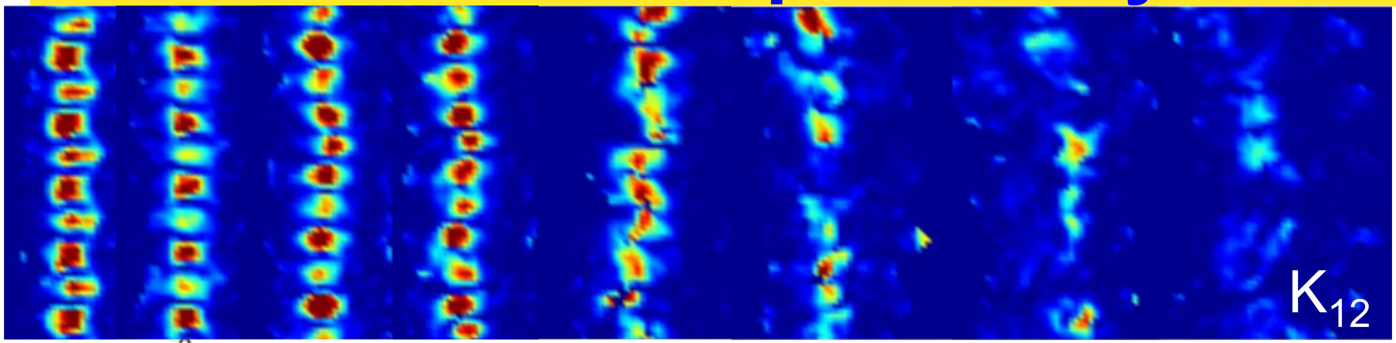
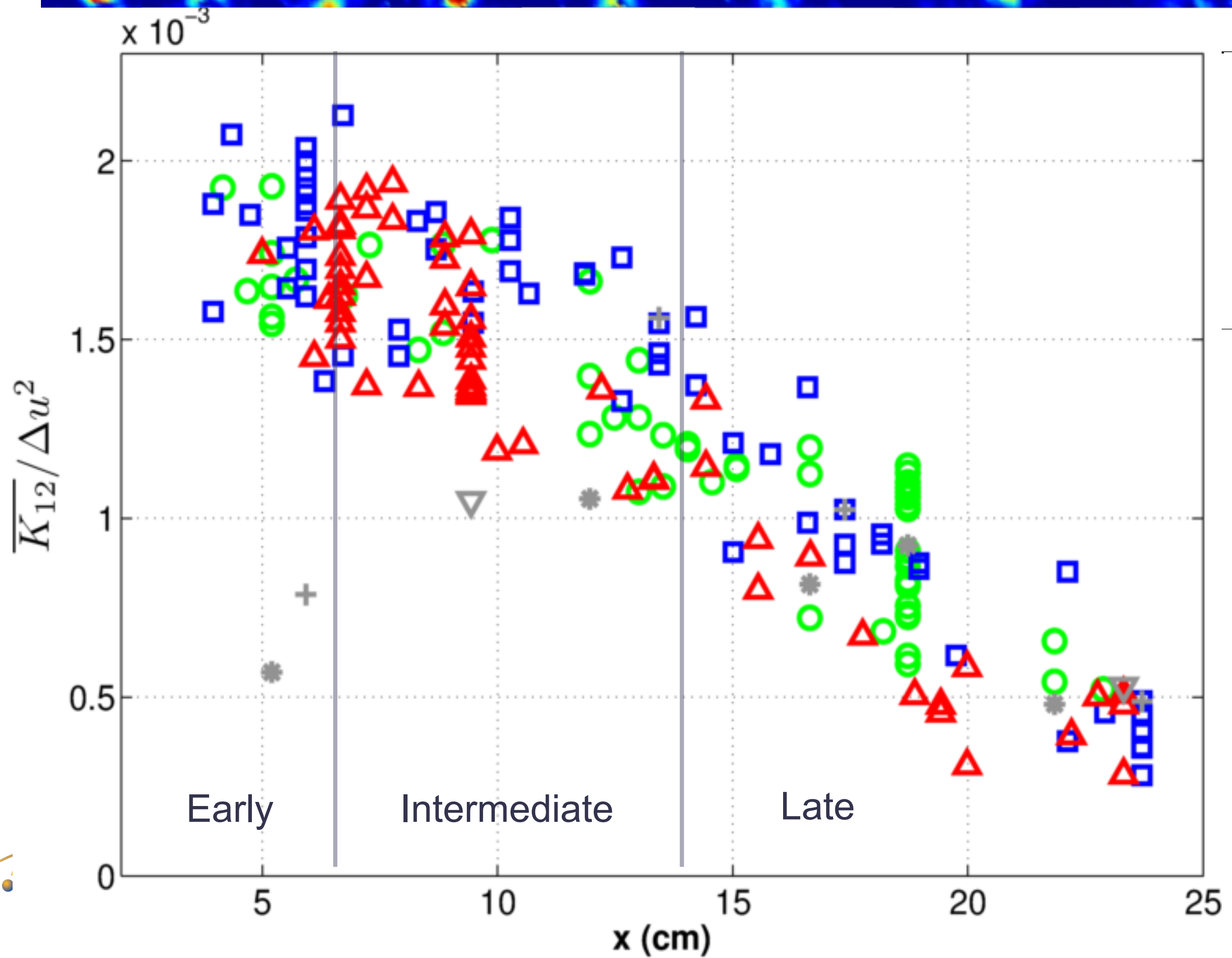
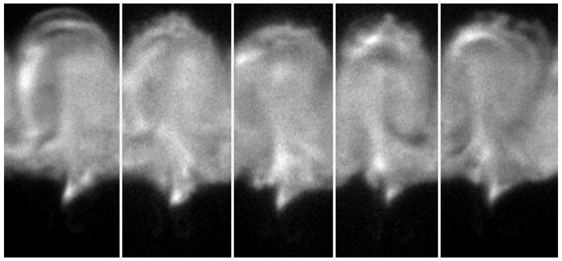
TKE ensemble averages match instantaneous at late times despite decay over time





475 μs (10.5 cm)



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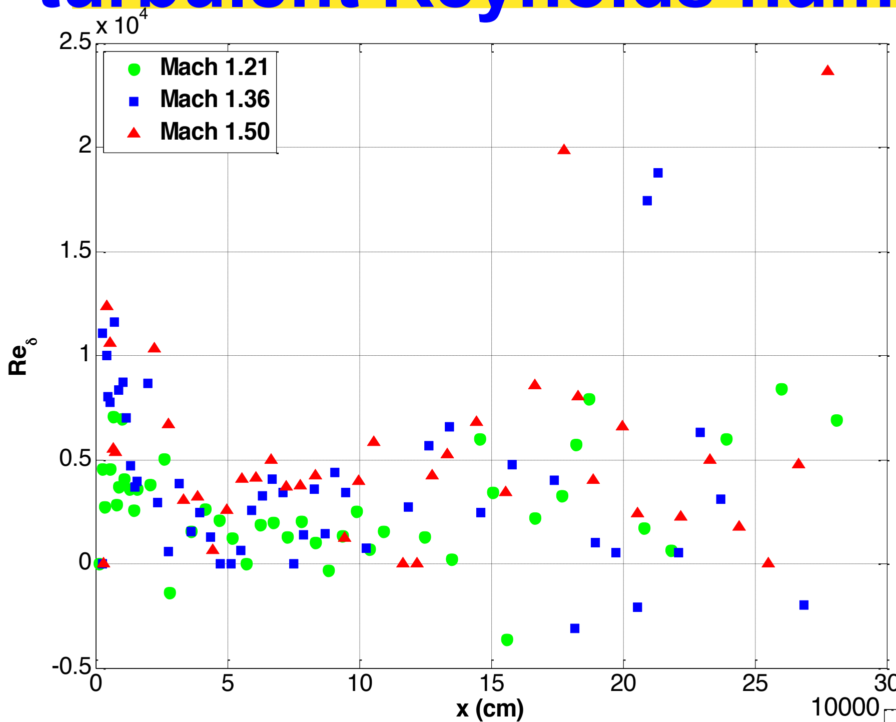
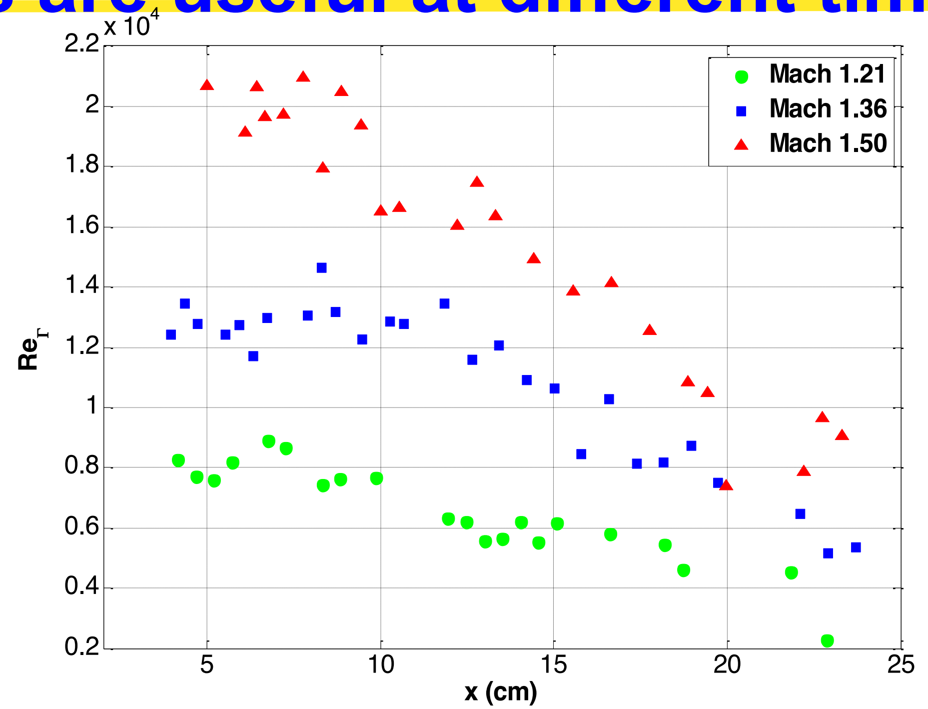
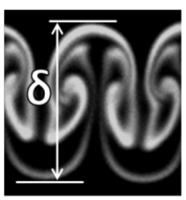
HST

Growth-rate Re is not a mixing metric; circulation and turbulent Reynolds numbers are useful at different times



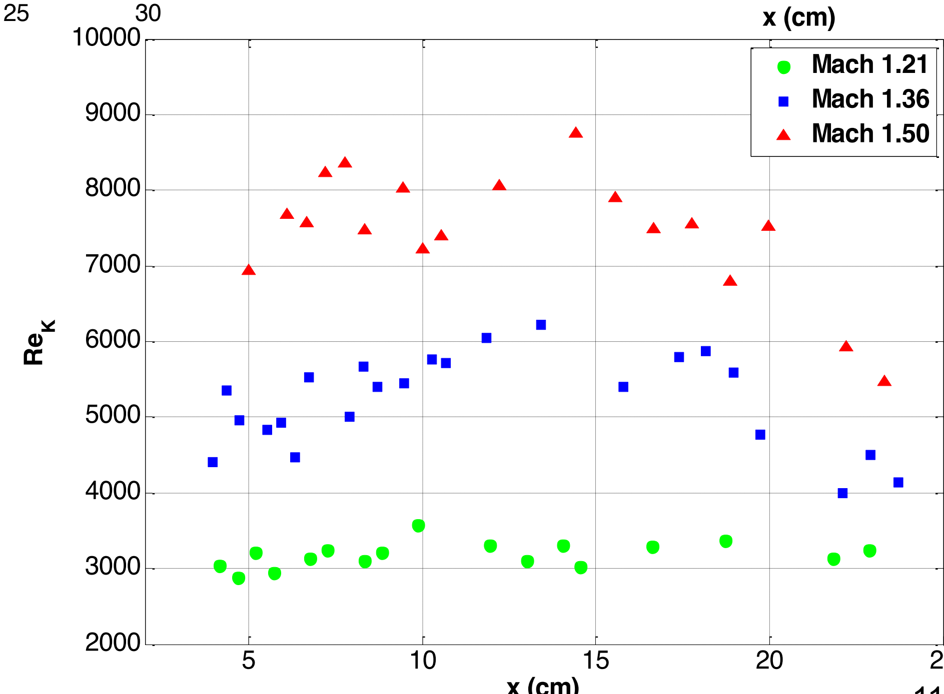




$$\mathrm{Re}_\delta = \delta\dot{\delta}/\nu$$

$$\mathrm{Re}_\Gamma = \Gamma/\nu$$

$$\mathrm{Re}_K = \sqrt{K_{12}}\,\delta/\nu$$



Early: $x \le 6$

Intermediate: $6 < x \le 13$

Late: $x > 13$

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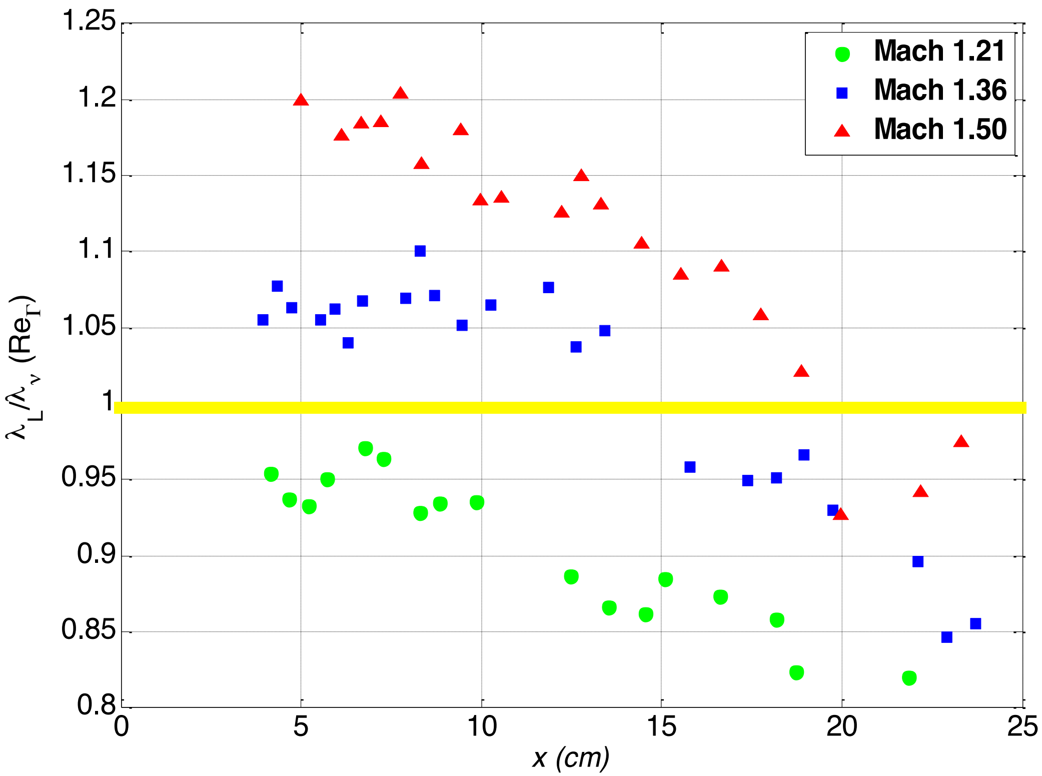
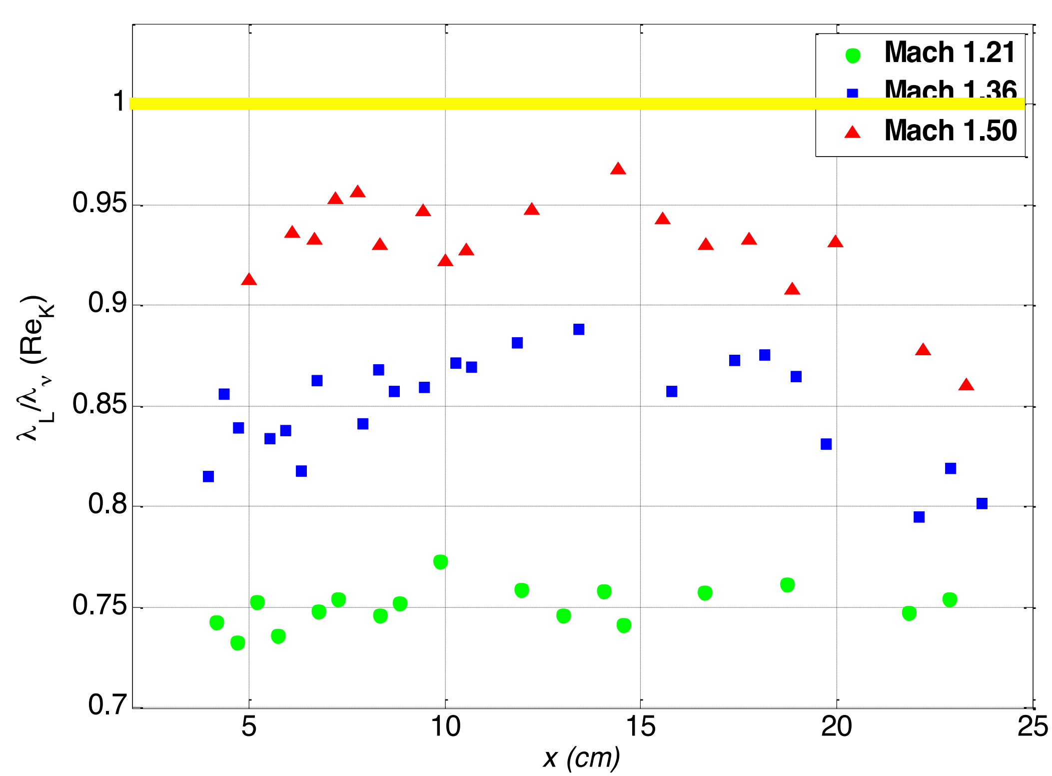
Does this flow meet criterion for a transition to turbulence?

Inner viscous: $\lambda_\nu = 50\delta\, \mathrm{Re}^{-3/4}$

Liepmann-Taylor: $\lambda_L = 5\delta\, \mathrm{Re}^{-1/2}$

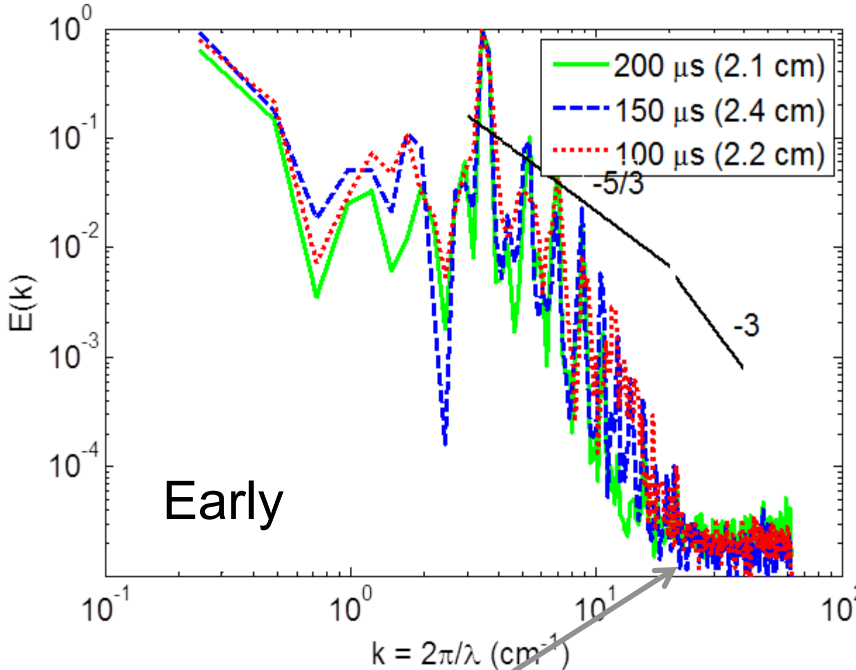
Transition criterion proposed by Dimotakis JFM 2000: $\dfrac{\lambda_L}{\lambda_\nu} > 1$

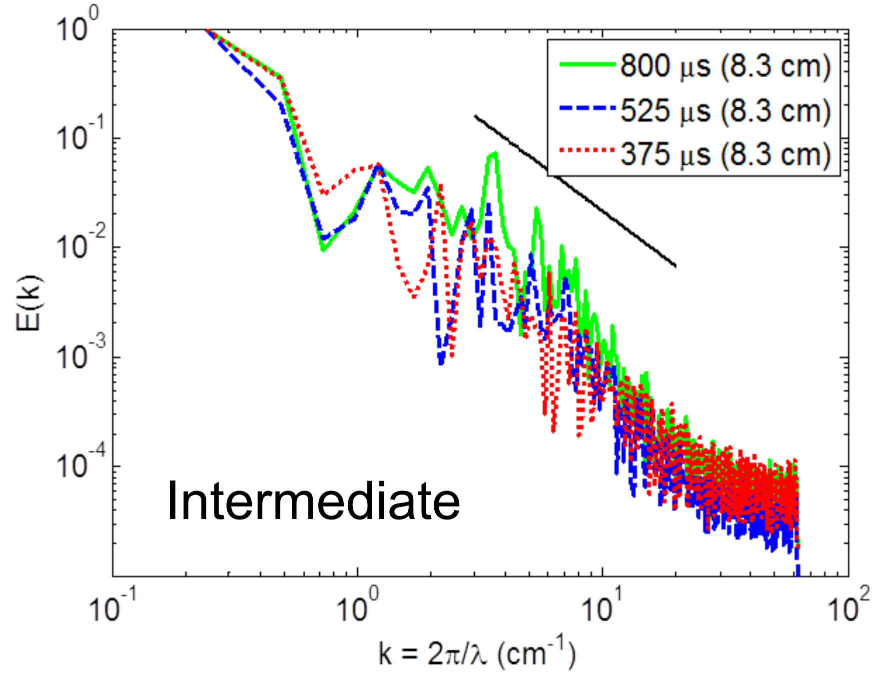




HST

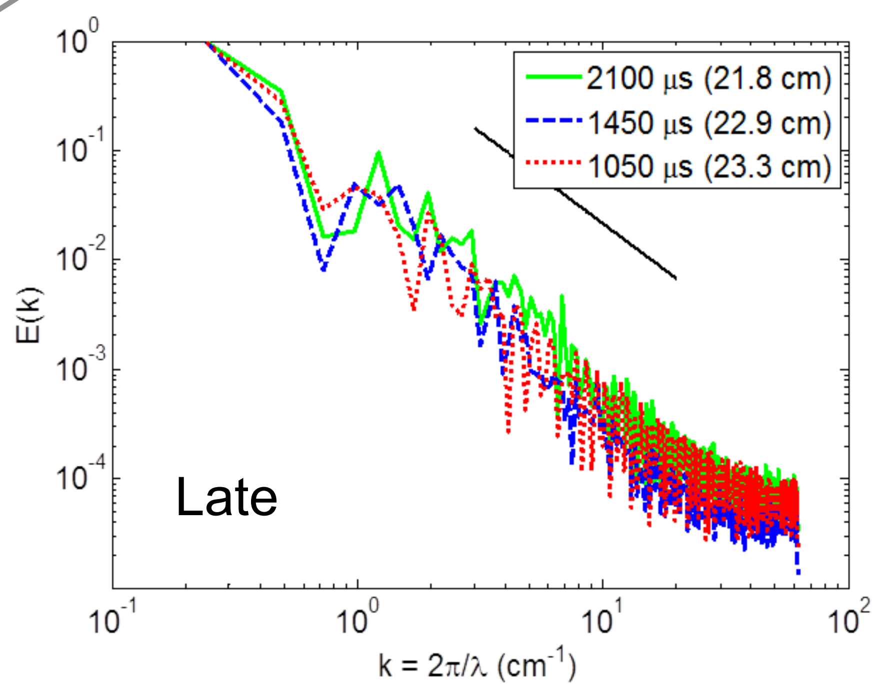
Power spectra of the density field show a transition of the flow to smaller scales





Noise Floor: k~30 mm^-1

(λ~0.209 mm or 4 pixels)



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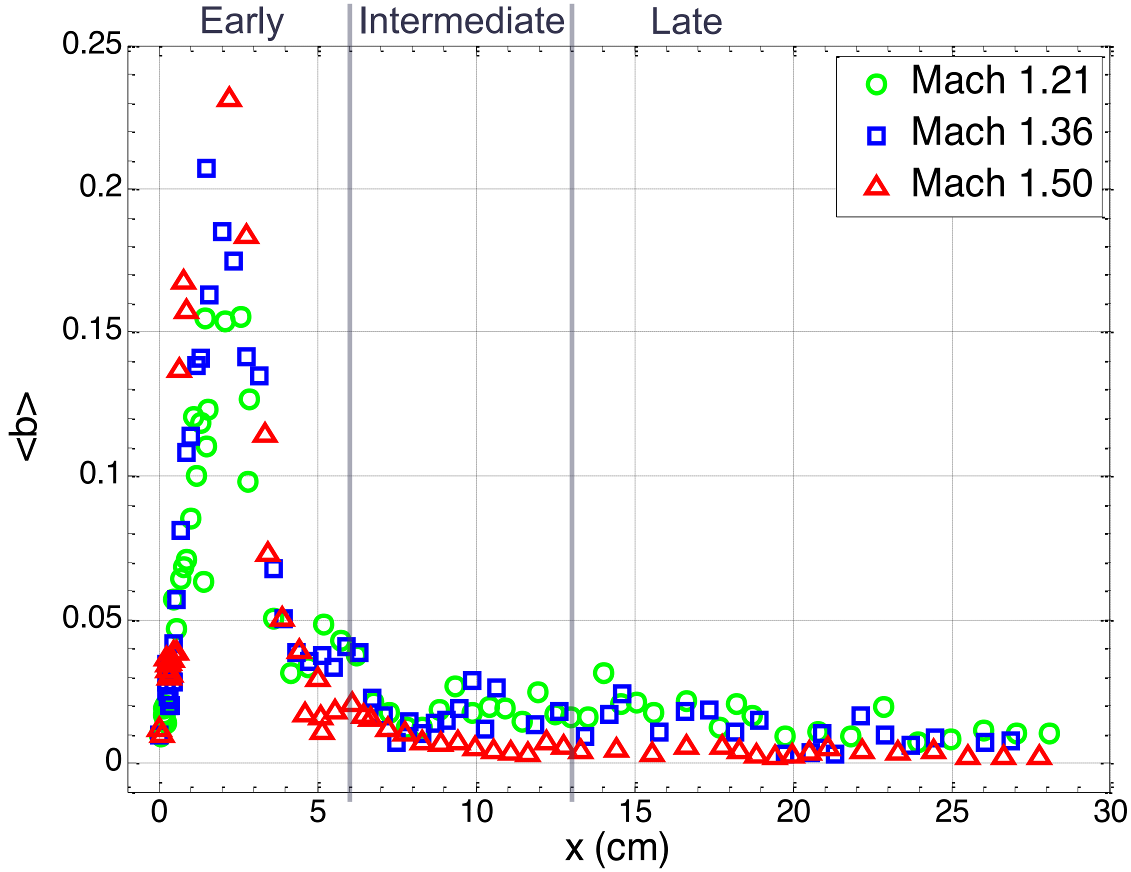
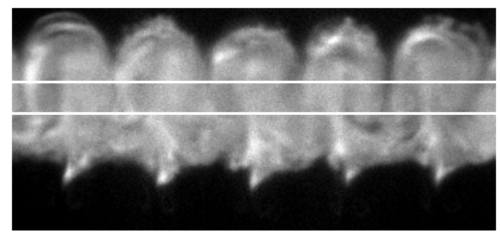
The density-specific-volume correlation is a multiplier in the production term of the mass flux equation



b can be calculated using mean or fluctuating quantities:

$$\boxed{b = -\overline{\rho' \left(\frac{1}{\rho}\right)'} = \bar{\rho}\,\overline{\left(\frac{1}{\rho}\right)} - 1}$$



Over the middle 20% region

$$\boxed{b = \overline{\rho(x,y)}\,\overline{\left(\frac{1}{\rho}\right)(x,y)} - 1}$$

Provides a measure of the amount of mixedness (low value is well mixed).

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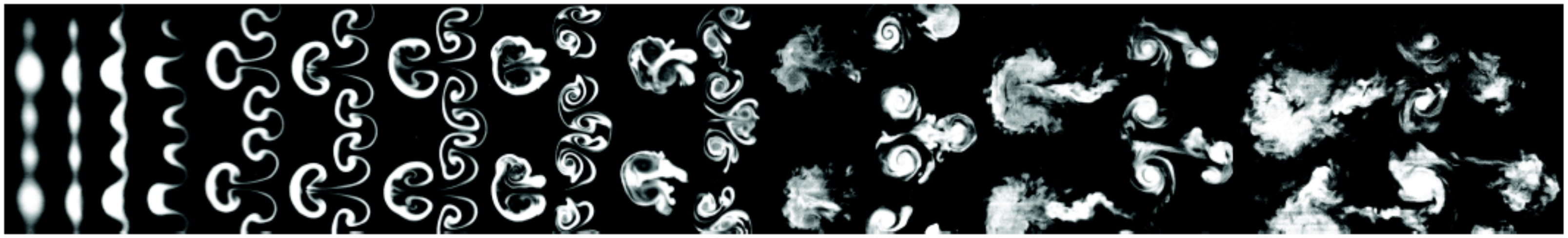
What if we change the modes of the initial conditions?

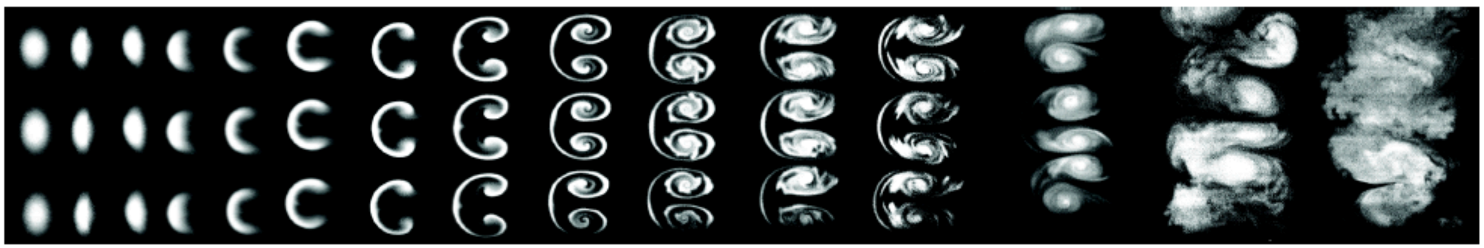
Mach 1.2 shock

MM



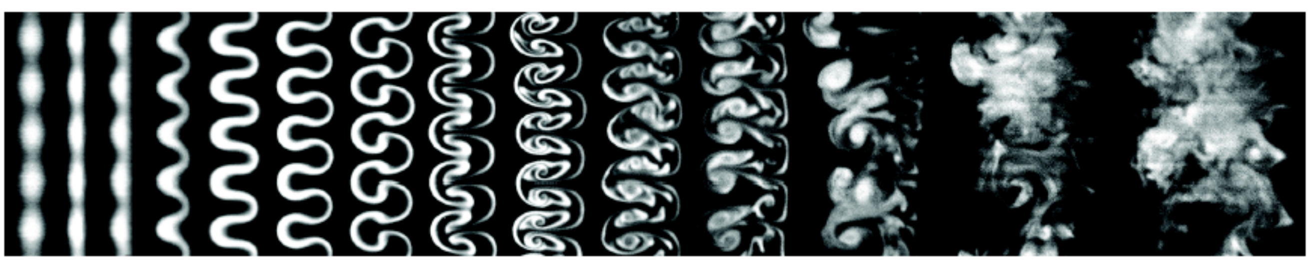
t (t*)
0 (0)
15 (0.11)
45 (0.32)
95 (0.67)
215 (1.52)
265 (1.87)
365 (2.57)
515 (3.63)
765 (5.40)
1115 (7.86)
1415 (9.98)
2265 (15.98)

LW



t (t*)
0 (0)
10 (0.11)
25 (0.29)
65 (0.75)
115 (1.33)
165 (1.90)
215 (2.47)
315 (3.62)
465 (5.34)
665 (7.64)
915 (10.51)
1365 (15.68)
1765 (20.27)
2065 (23.72)
2265 (26.02)

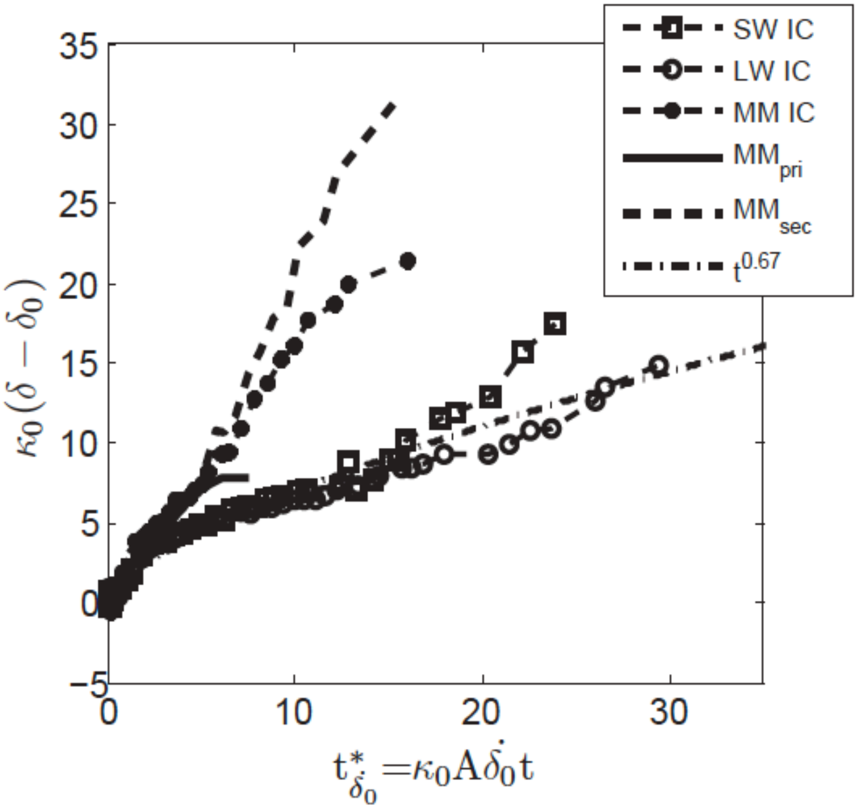
SW



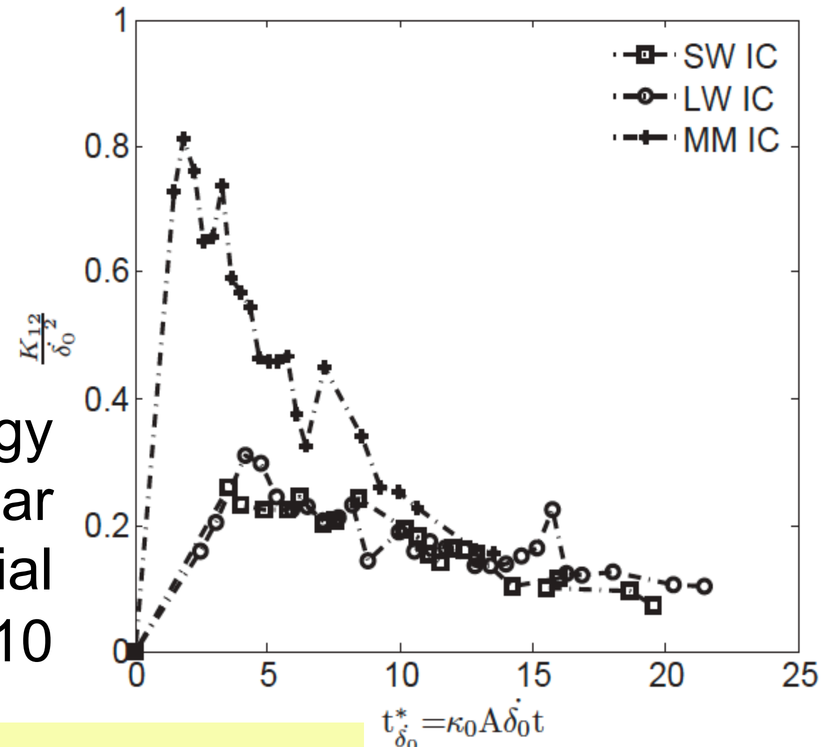
t (t*)
0 (0)
13 (0.11)
25 (0.22)
75 (0.67)
150 (1.33)
200 (1.77)
270 (2.40)
400 (3.55)
600 (5.32)
850 (7.54)
1150 (10.20)
1750 (15.52)
2300 (20.40)
2700 (23.95)

Balasubramanian et al. JoT 2013

Can we change the initial conditions and still get the same mixing behavior?



The large-scale mixing, as quantified by the mixing width, follows similar growth rates for the single-mode initial conditions, but not the multi-mode!



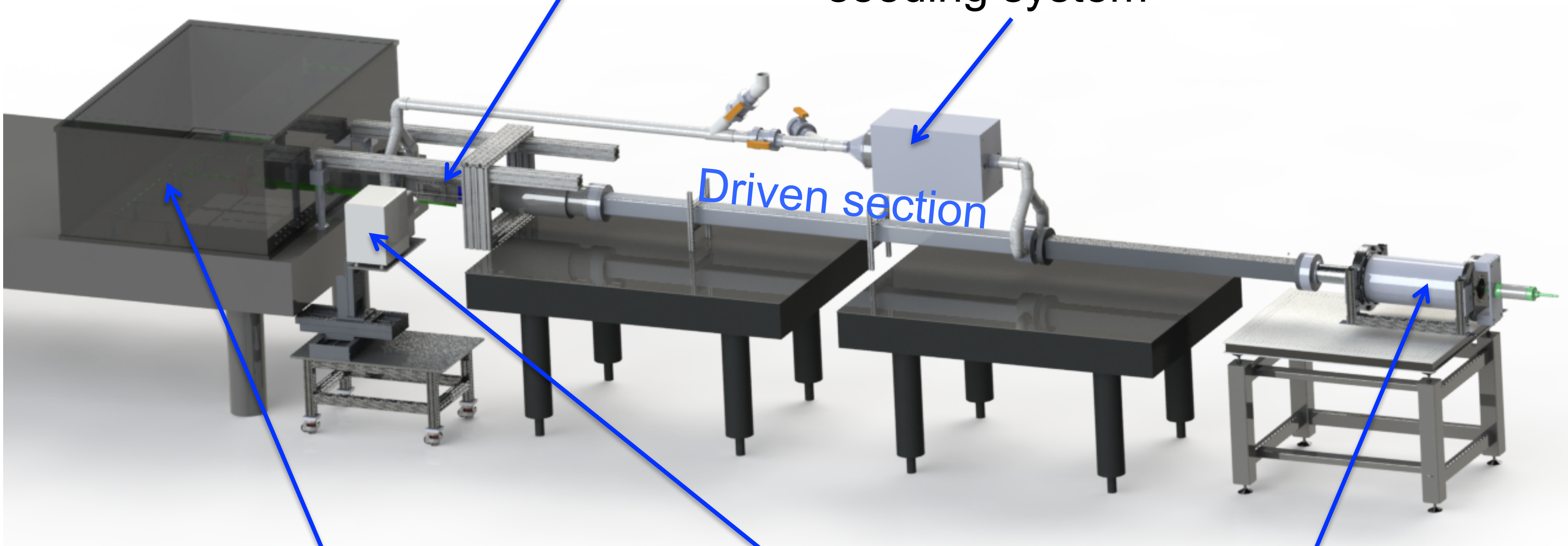
The turbulent kinetic energy appears to decay to similar values for each initial condition after t*=10

The jury is still out on how simple it will be to incorporate initial conditions effects into modeling!

The HST has been retrofitted to study shock-driven multiphase flows using PIV/Accelerometry

Test section

Continuous-flow particle seeding system



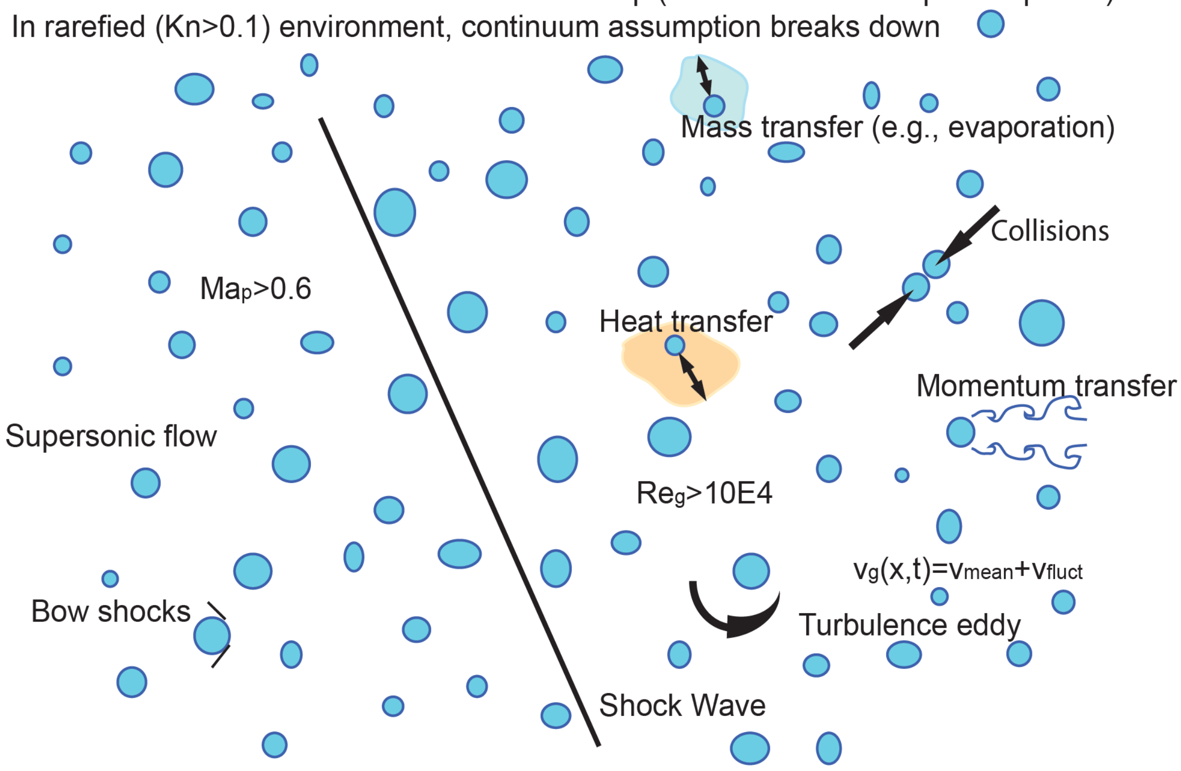
High-speed camera

8 light pulses @ 532 nm

Driver Section: Membrane-free, pneumatic

Ejecta transport experiments are targeting velocity and acceleration fields

Velocity field is unsteady, turbulent, with shocks and rarefactions ($Re_p>100$, $Ma_p>0.6$)
Thermal Effects (particles & gas are not in thermal equilibrium)
Particles can be different sizes, non-spherical, and deform
Particles can change size (evaporation, breakup, deformation)
Particles interact with each other and can clump (dense vs. dilute dispersed phase)
In rarefied (Kn>0.1) environment, continuum assumption breaks down



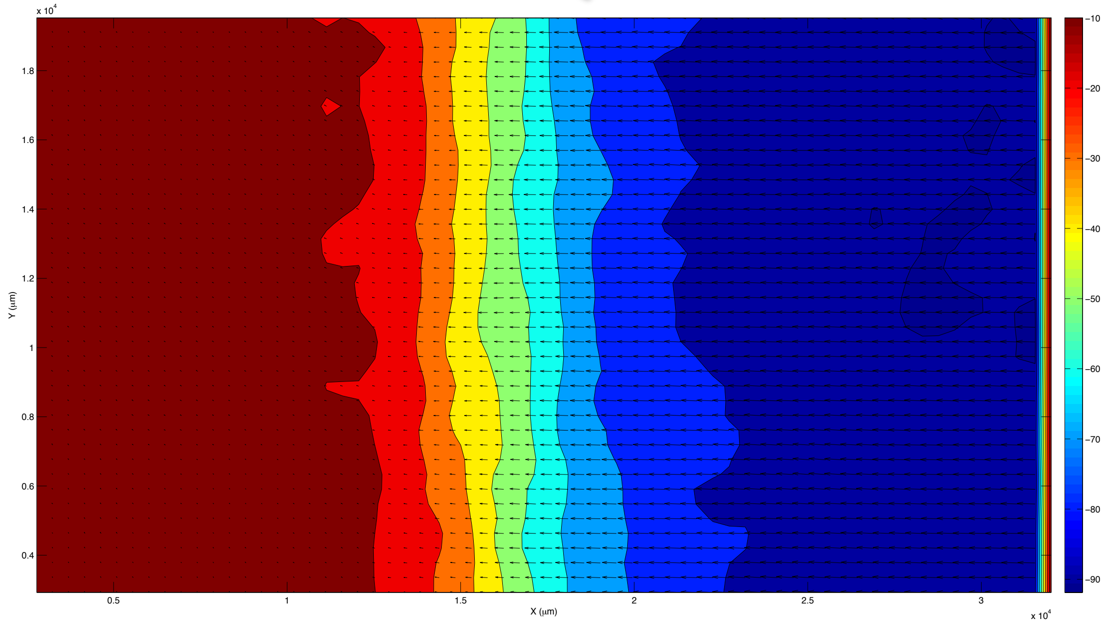
Parametric studies:

- Particle size distributions (fixed, solid & liquid non-evaporating)
- Incident shock Mach number (improving test section for up to Mach 5)
- Particle density/carrier phase density
- Particle shape (non-spherical)
- Particle size over time (evaporating) (requires real-time sizing diagnostic, to be developed/installed)

HST

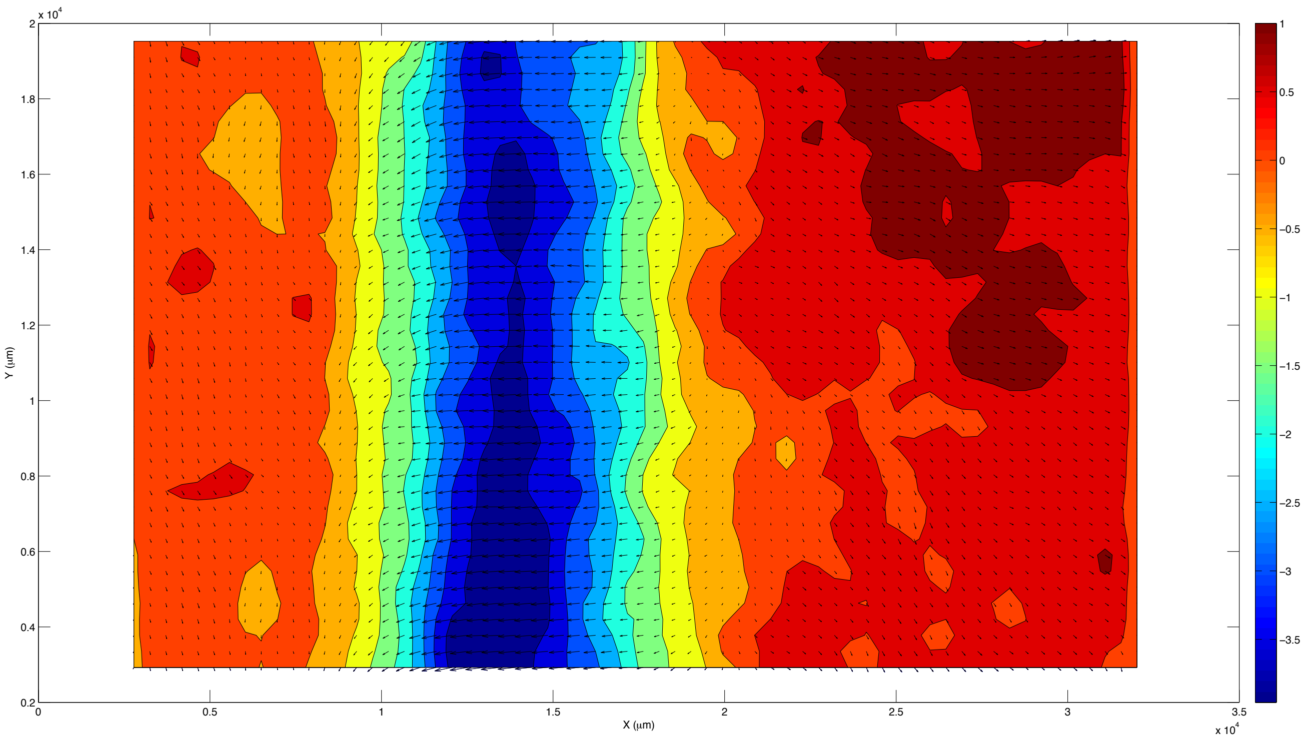
Velocity and acceleration fields have been captured at the time of shock passage through the particle field

Shock direction



Velocity field (m/s)

Shows particles accelerated to 90 m/s with Mach 1.1 shock (blue) and unaccelerated region (dark red).



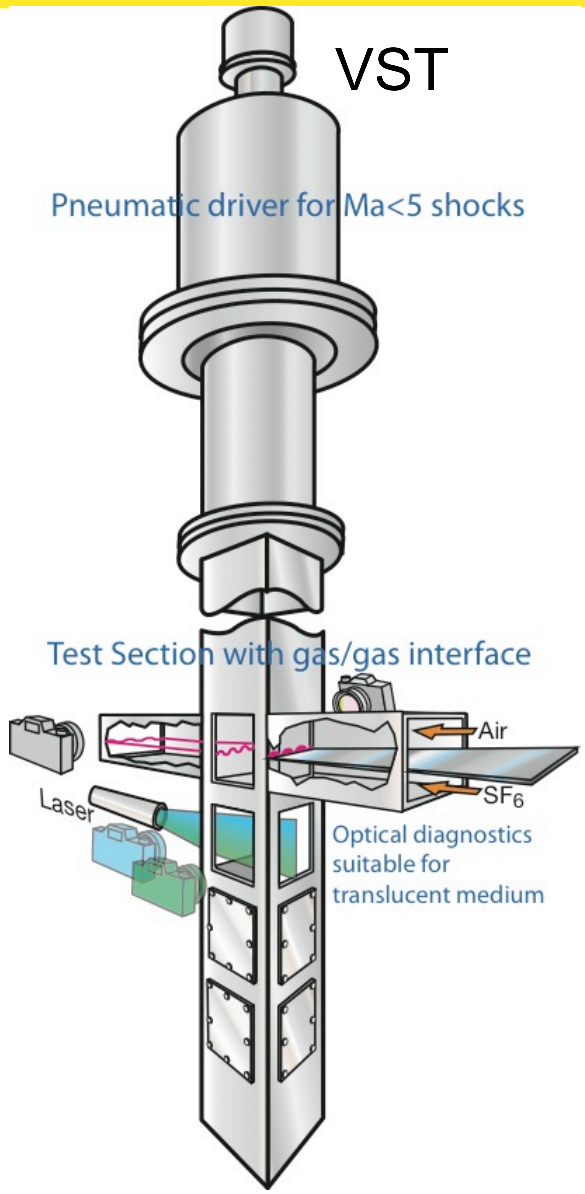
Acceleration Field (m/s^2)

Shows region of maximum acceleration (blue).

This spatial and temporal resolution of PIVA is promising because we are capturing the accelerations of the particles up to the jump velocity.

Vertical Shock Tube: Richtmyer-Meshkov Instability Studies

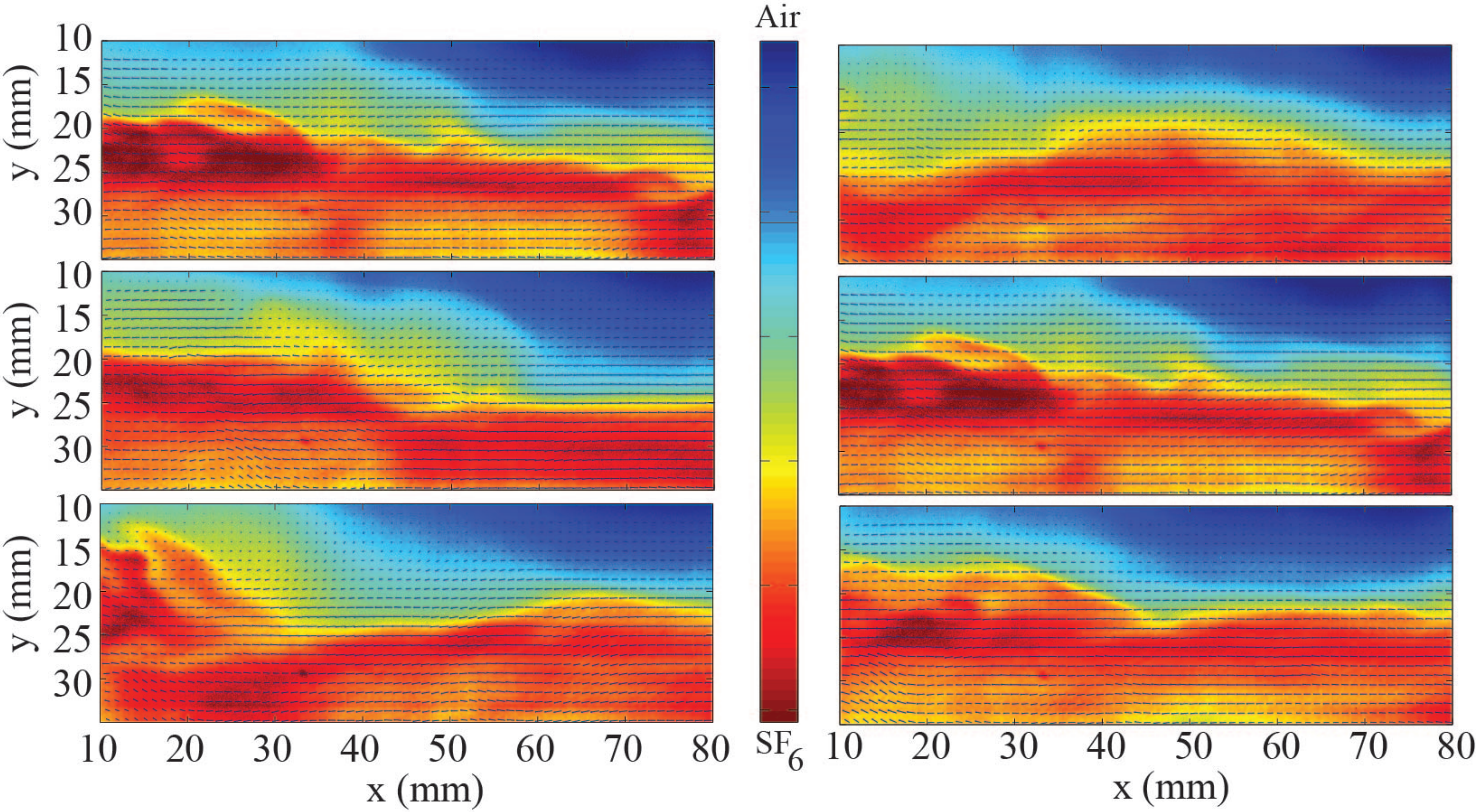
- **Physics Parameters:**
  - Mach number (1<Ma<3, with current diagnostics)
  - **Single-interface turbulent miscible mixing**
  - Multimode 3-D Initial Conditions (statistically stationary)
  - Range of Atwood numbers possible
- **First Measurements:**
  - *Simultaneous* velocity and density field measurements
  - Mean and fluctuating velocity and density fields
- **Modeling Parameters**
  - Reynolds stress
  - turbulent kinetic energy (K)
  - density specific-volume correlation (b)
  - turbulent mass flux (a)



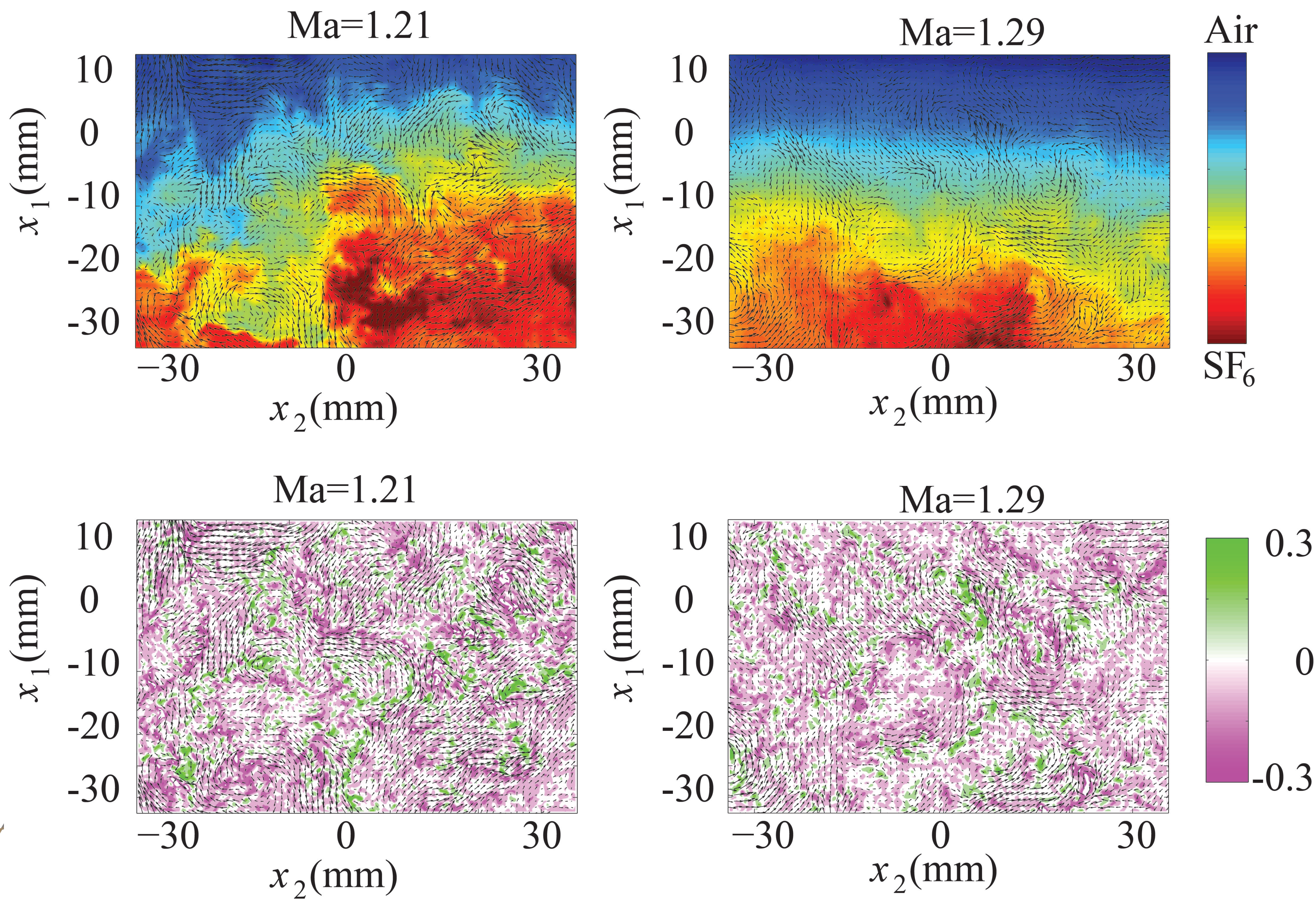
To date we use up to 3 RM experiments for model validation. Only 1 has anything other than an ill-defined mix width; All experiments are limited on details of initial conditions.

We create multimode initial conditions that can be characterized both statistically and instantaneously

Density and velocity fields of initial conditions

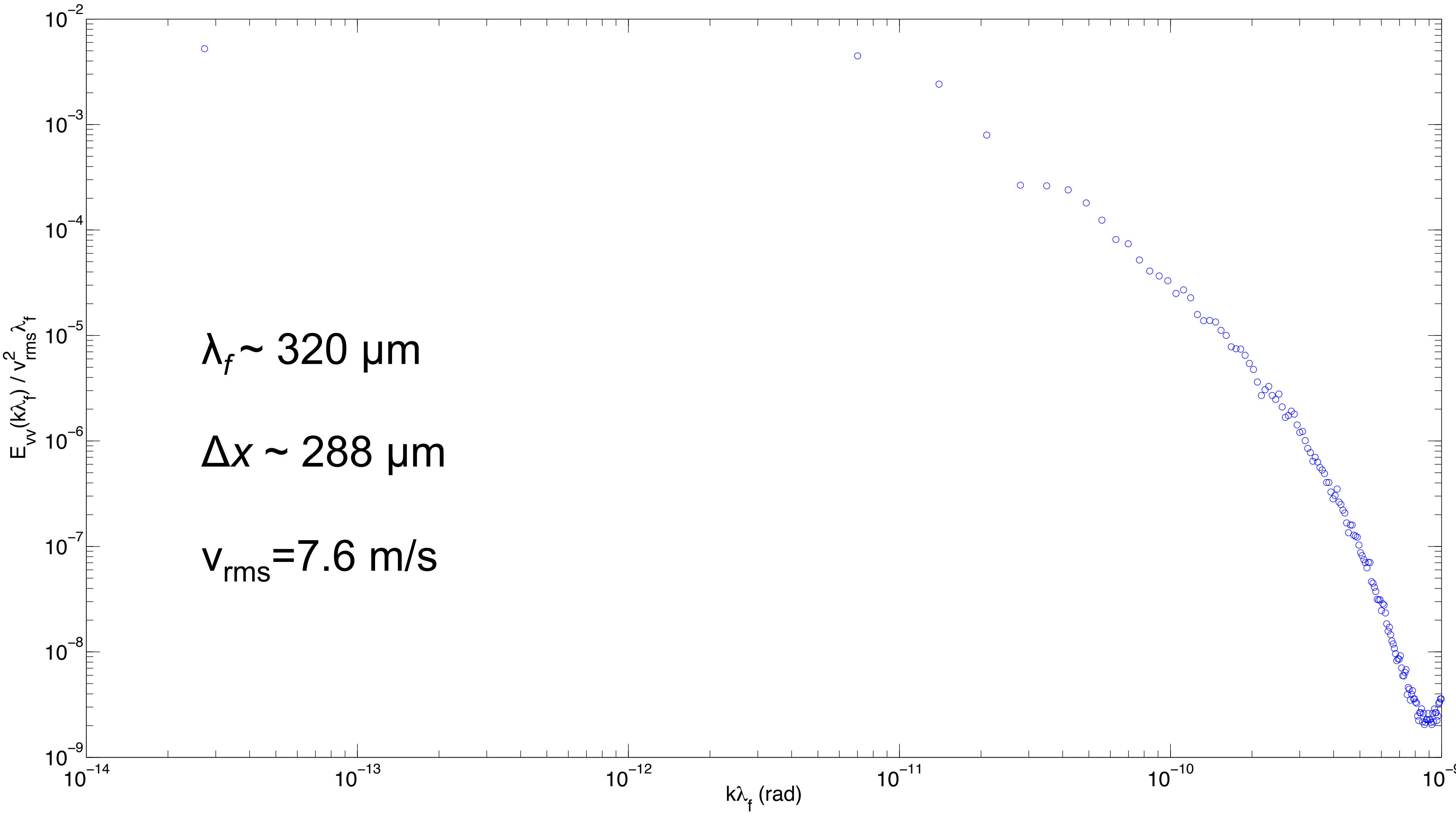


780 μs after shock, the flow exhibits stronger mixing transition than we saw in single-mode experiments



VST

This cascade is also visible in the velocity spectrum that shows an inertial range



780 μs after shock

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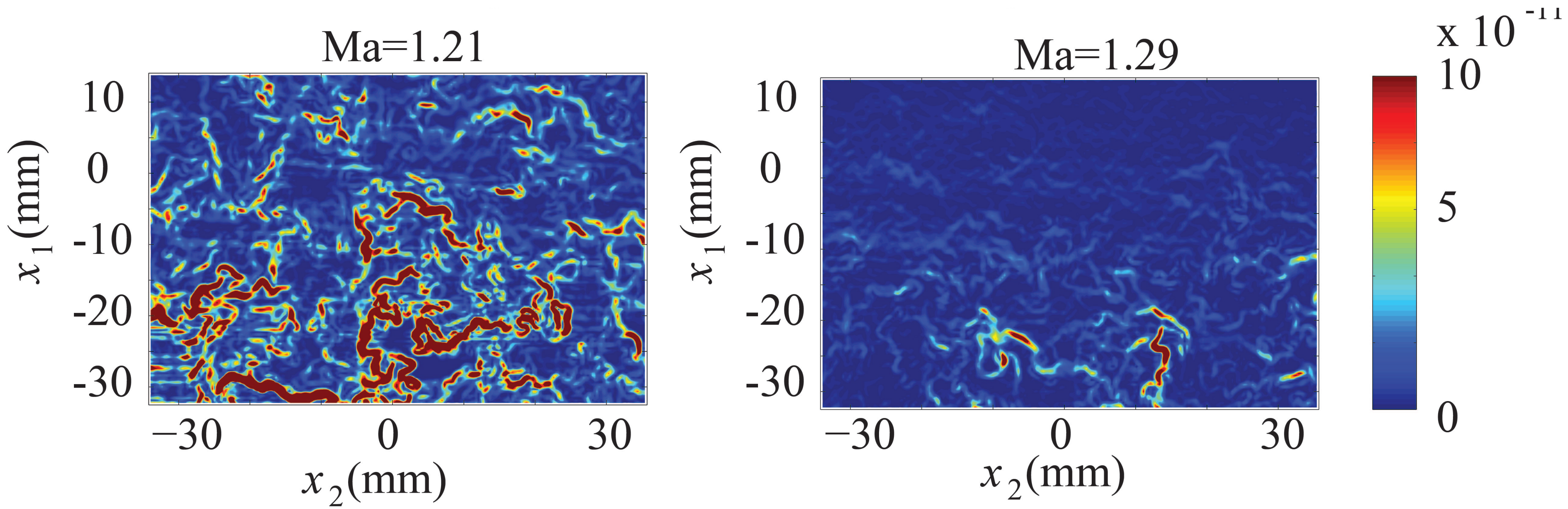
VST

Instantaneous mixing rates show slightly increased mixing at the higher Mach number

$$\chi = D\left(\nabla c_v \cdot \nabla c_v\right)$$

$\overline{\chi}_{1.21} = 1.4\times 10^{-11}\,\mathrm{s}^{-1}$ $\overline{\chi}_{1.29} = 0.6\times 10^{-11}\,\mathrm{s}^{-1}$



The VST has just been commissioned this summer. Our first studies will examine Ma and initial conditions effects on turbulence quantities.

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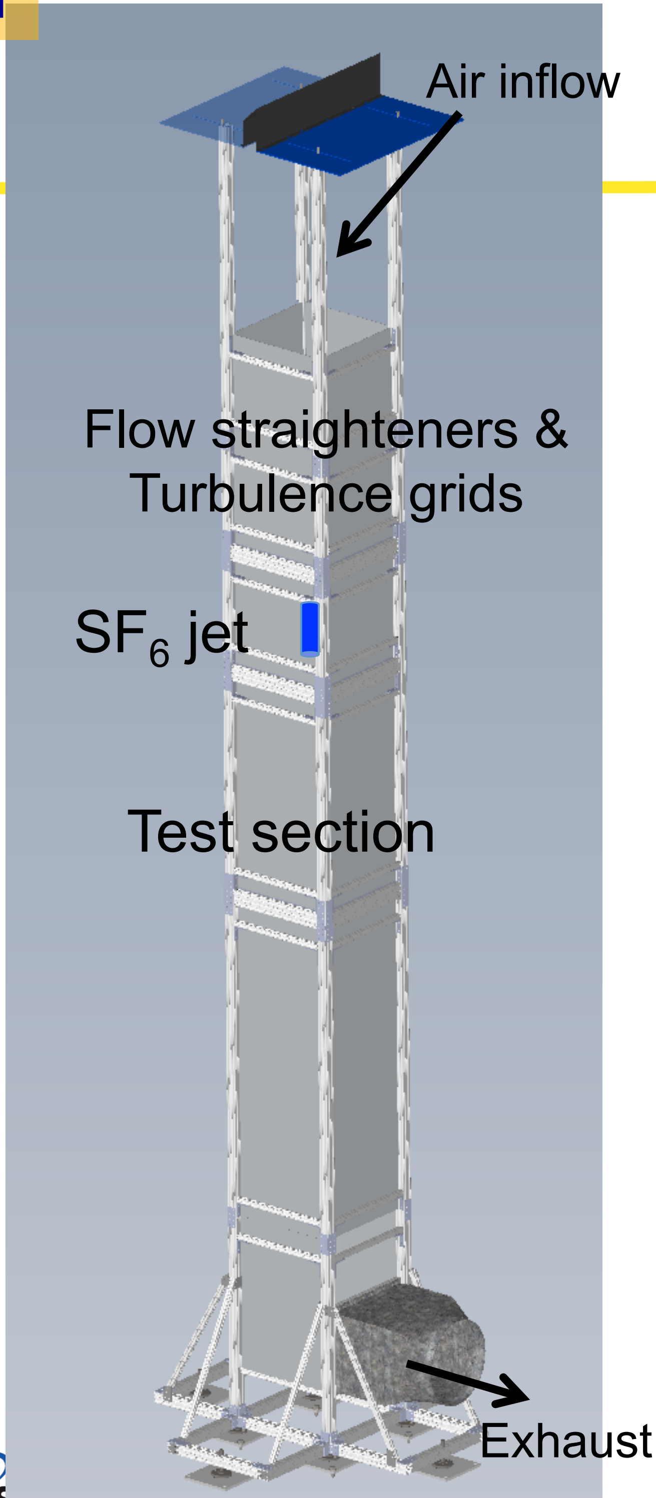
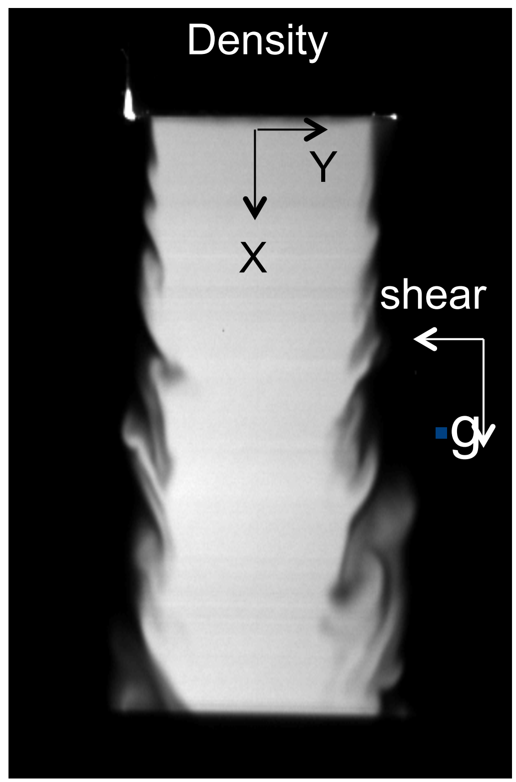


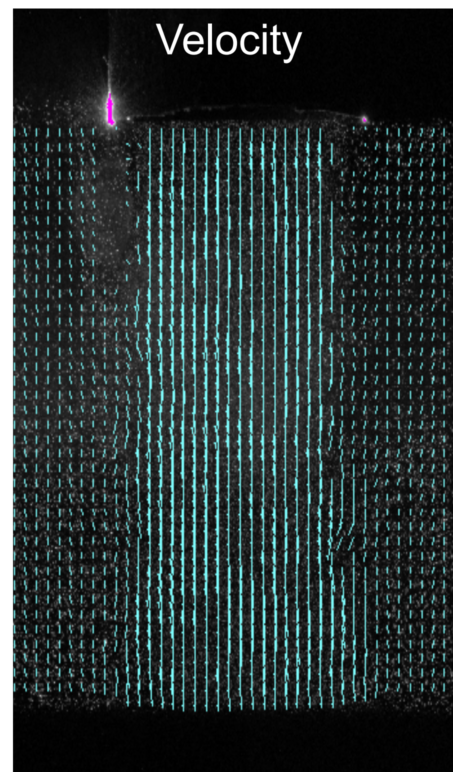
Turbulent Mixing Tunnel

Subsonic facility allows variation of flow turbulence levels, Reynolds number and Atwood number.

Simultaneous measurement techniques (0.5 mm resolution in velocity and density fields):

- 2D Planar Laser-Induced Fluorescence (PLIF)
- 2D Particle Image Velocimetry (PIV)
- Favre averaging using 2000-4000 data sets (no spatial averaging)





First Experiments: Set up multiple flow scenarios varying At and Re to see if buoyancy effects are observable

Case	Flow rate, lpm	Re_{jet}	Density, kg/m^3	At	Ri	Sc
SF_6 case 1	6	6900	4.1	0.62	0.025	0.15
SF_6 case 2	2.5	2600	4.1	0.62	0.17	0.15
Air case 1	6	1600	1.13	0.09	0.005	0.8

$$Re_{jet} = \frac{\rho_{jet} \cdot \Delta U \cdot d}{\eta_{jet}}$$

$$At = \frac{\rho_{jet} - \rho_{air}}{\rho_{jet} + \rho_{air}}$$

$$Ri = \frac{g \cdot d \cdot (\rho_{jet} - \rho_{air})}{\rho_{jet} \cdot \Delta U^2}$$

$$Sc = \frac{\eta_{jet}}{\rho_{jet} \cdot D}$$

ΔU - difference between jet exit and background flow velocities

d - jet diameter (d = 1.1 cm)

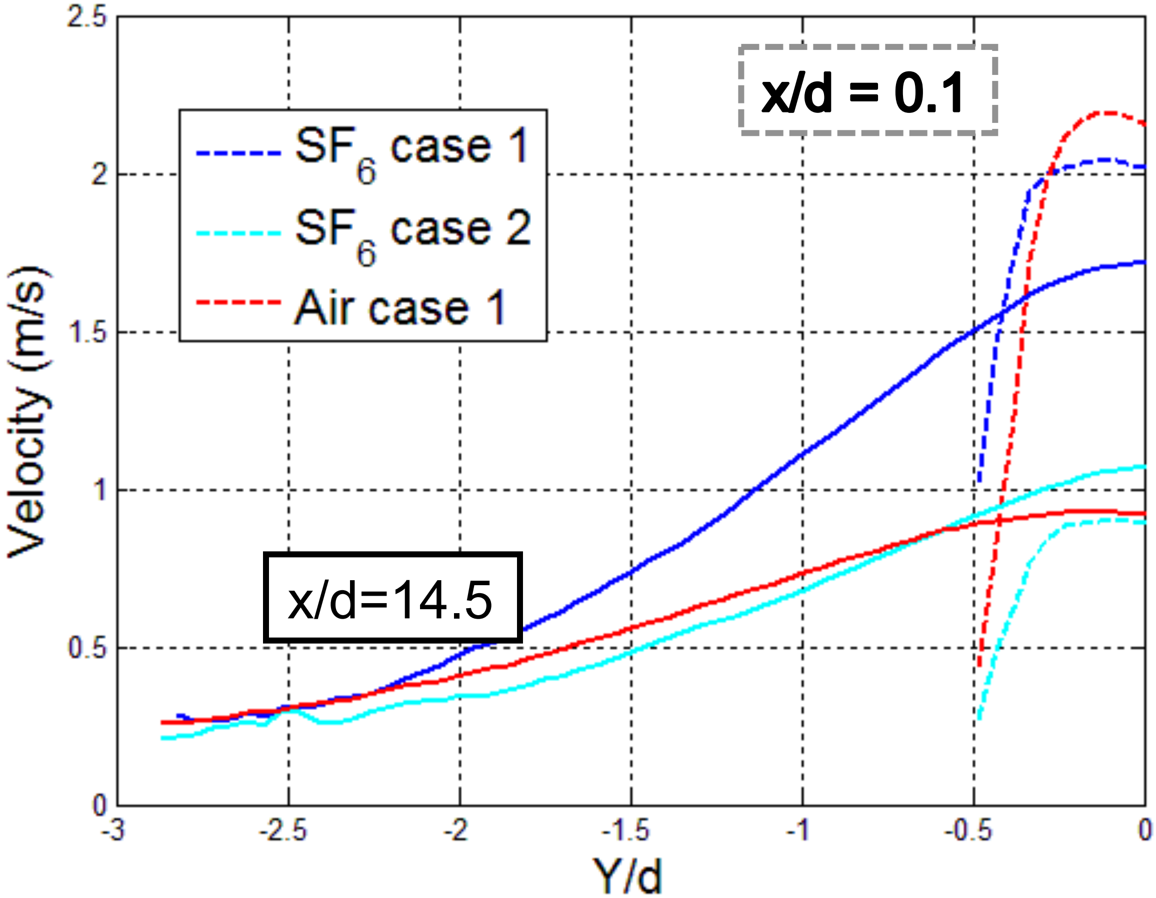
D - mass diffusivity

Measurements at:

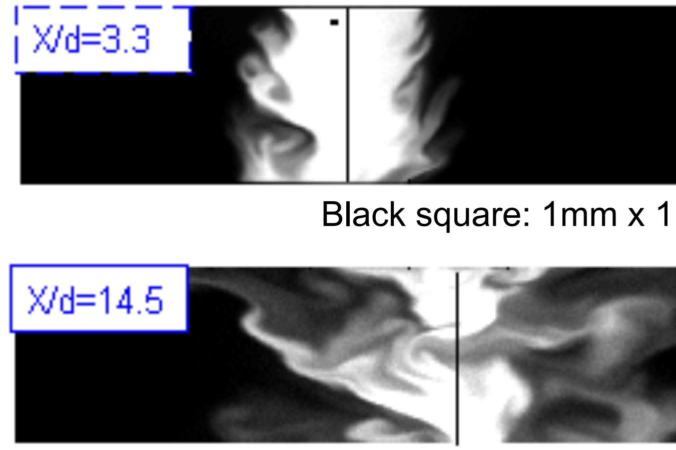
x/d = 3.3 – momentum dominated region

x/d = 14.5 – buoyancy dominated region

3 cases: Two matched flow rates and two matched At

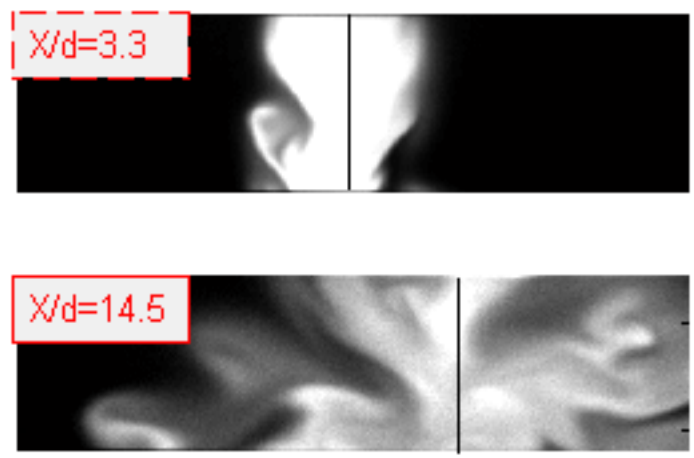


SF_6 Case 1



Black square: 1mm x 1mm

Air Case 1



Case	Flow rate, lpm	Re_{jet}	At
SF_6 case 1	6	6900	0.62
SF_6 case 2	2.5	2600	0.62
Air case 1	6	1600	0.09

$$\Delta x = \sqrt{D \Delta t}$$

$$\Delta x_{SF6} = 0.9\,\text{mm}$$

$$\Delta x_{air} = 1.0\,\text{mm}$$

$$\Delta x_{acetone} = 1.1\,\text{mm}$$

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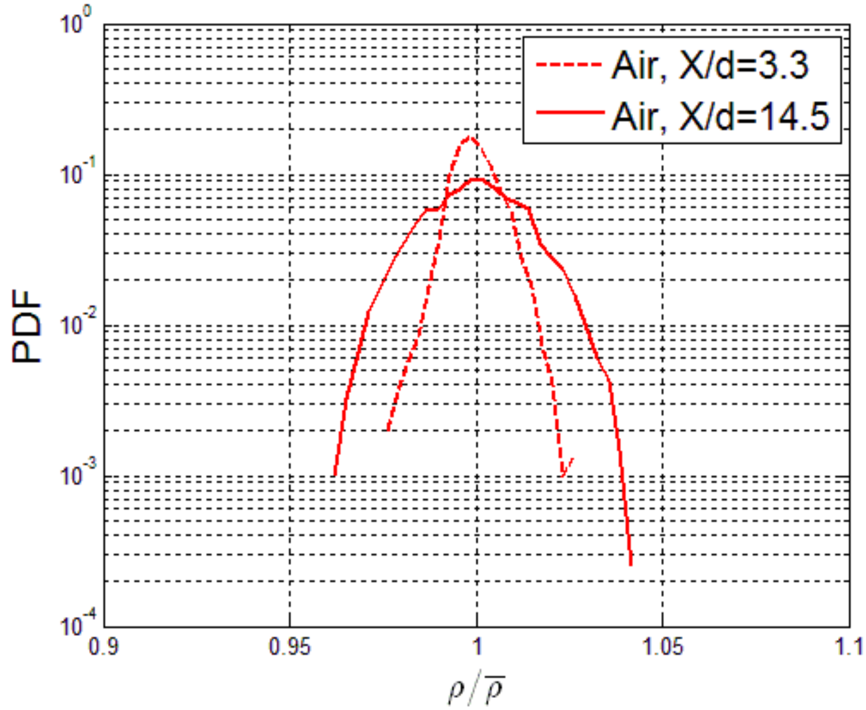
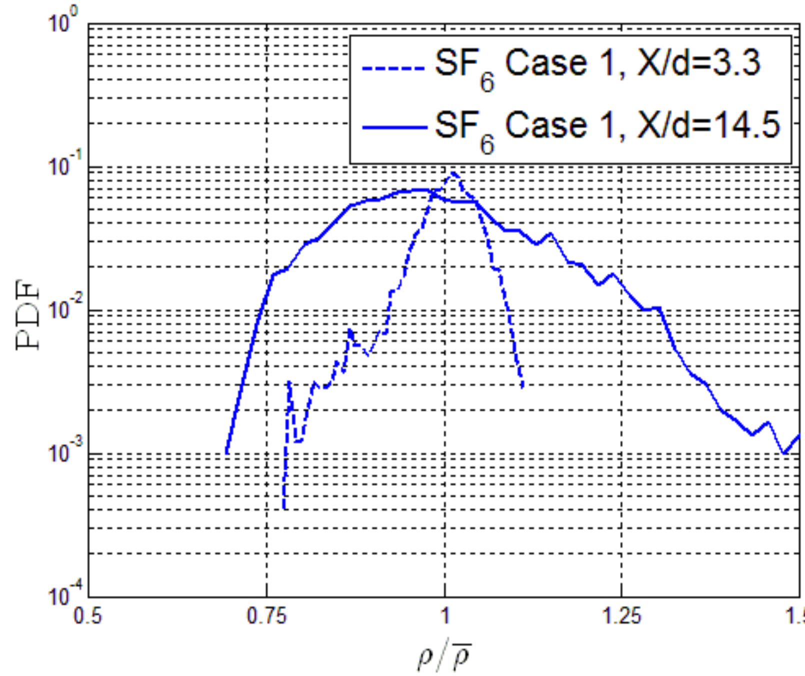
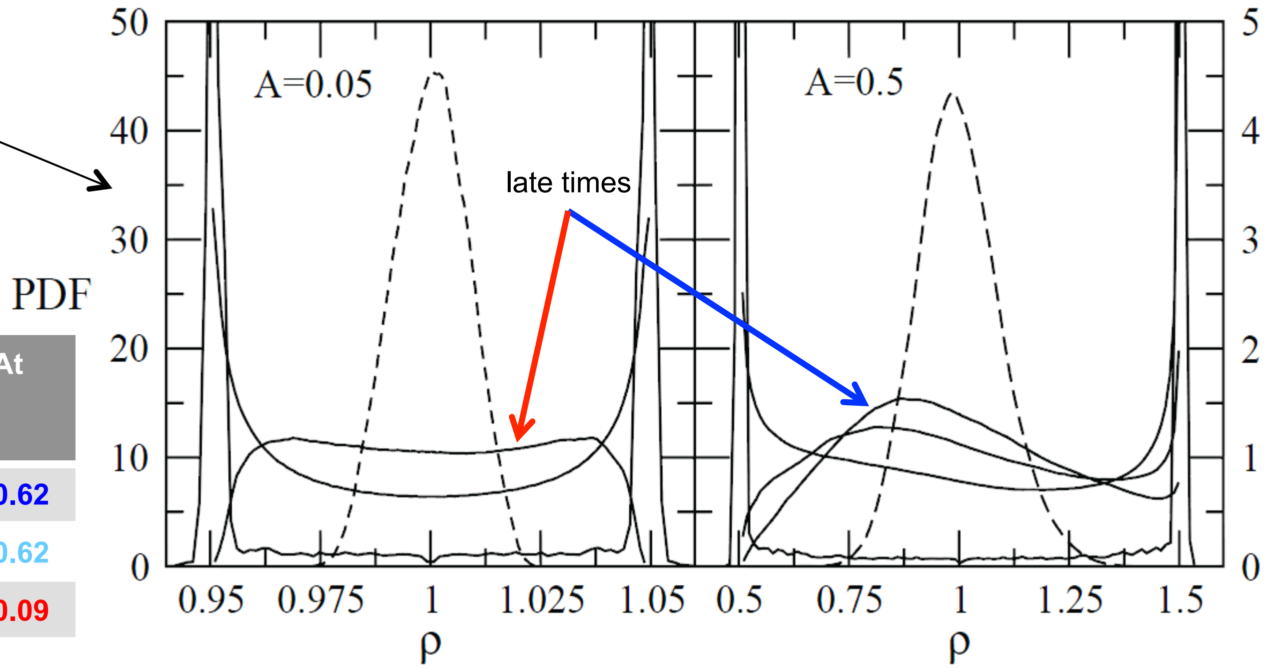
Density PDFs show expected effects of higher *At* and compare well to similar DNS conditions





DNS of homogeneous, variable density turbulent mixing



Livescu & Ristorcelli, *Advances in Turbulence XII*, Springer Proceedings in Physics 132, 2009

Case	Flow rate, lpm	Re_{jet}	At
SF_6 case 1	6	6900	0.62
SF_6 case 2	2.5	2600	0.62
Air case 1	6	1600	0.09

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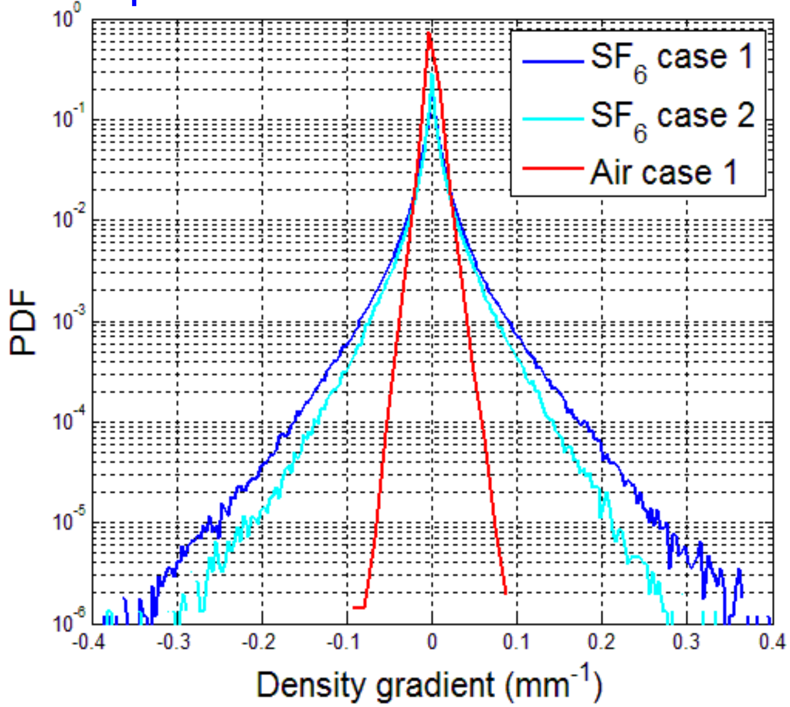
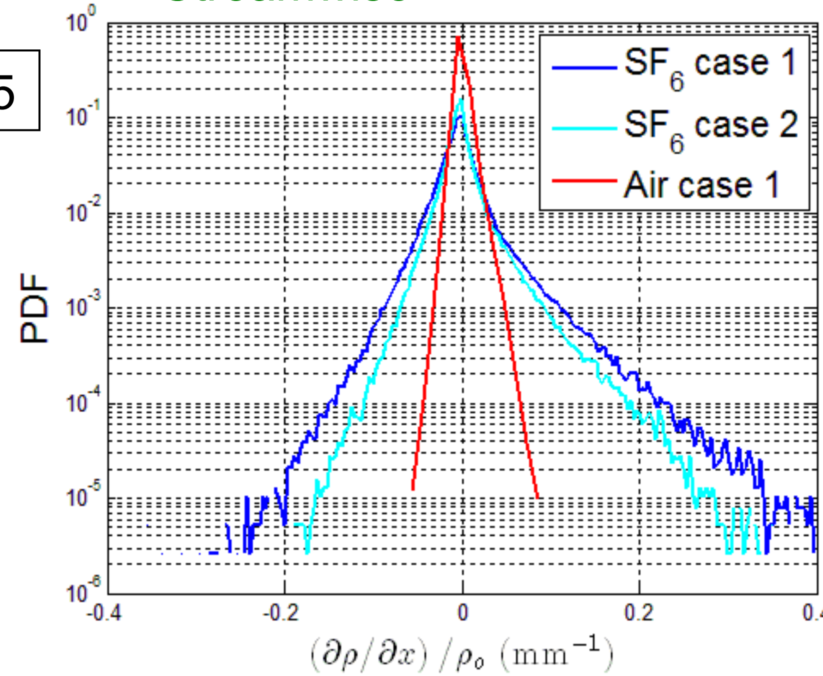
TMT

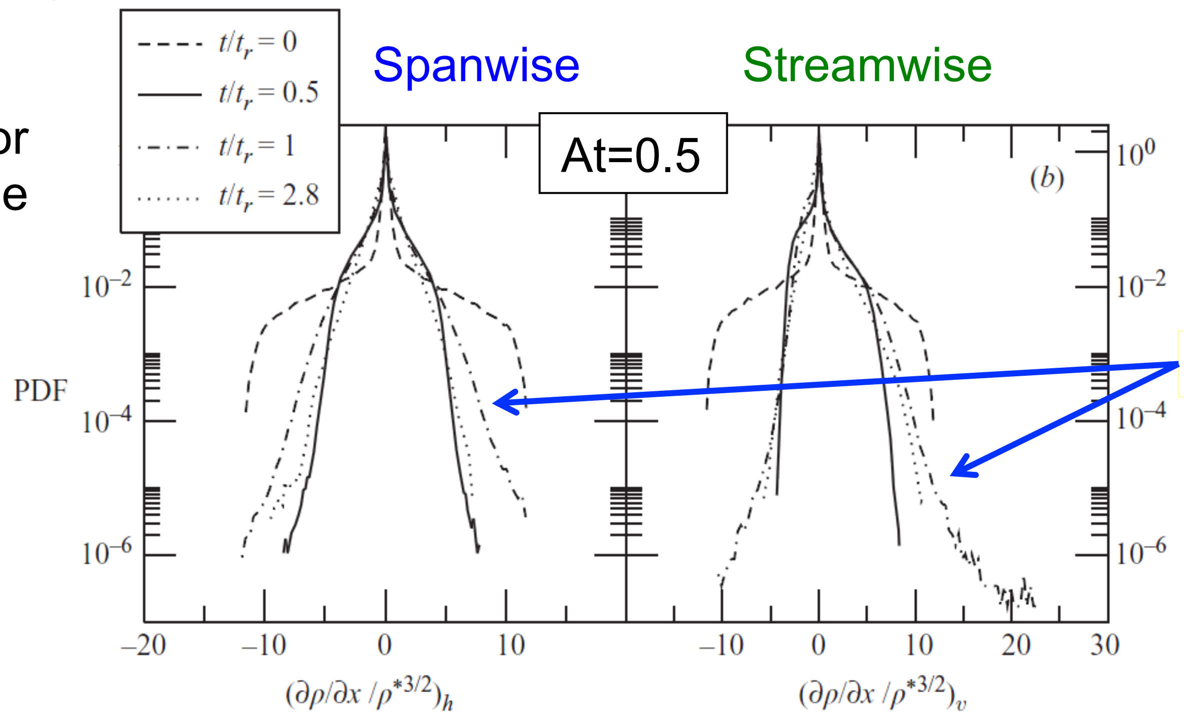
Density gradient PDFs indicate increased molecular mixing in higher *At* cases

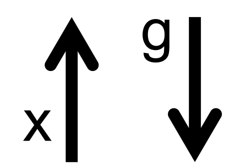


x/d=14.5



DNS results for high At case





late times

Livescu & Ristorcelli, JFM, 2008

Case	Flow rate, lpm	Re_{jet}	At
SF_6 case 1	6	6900	0.62
SF_6 case 2	2.5	2600	0.62
Air case 1	6	1600	0.09

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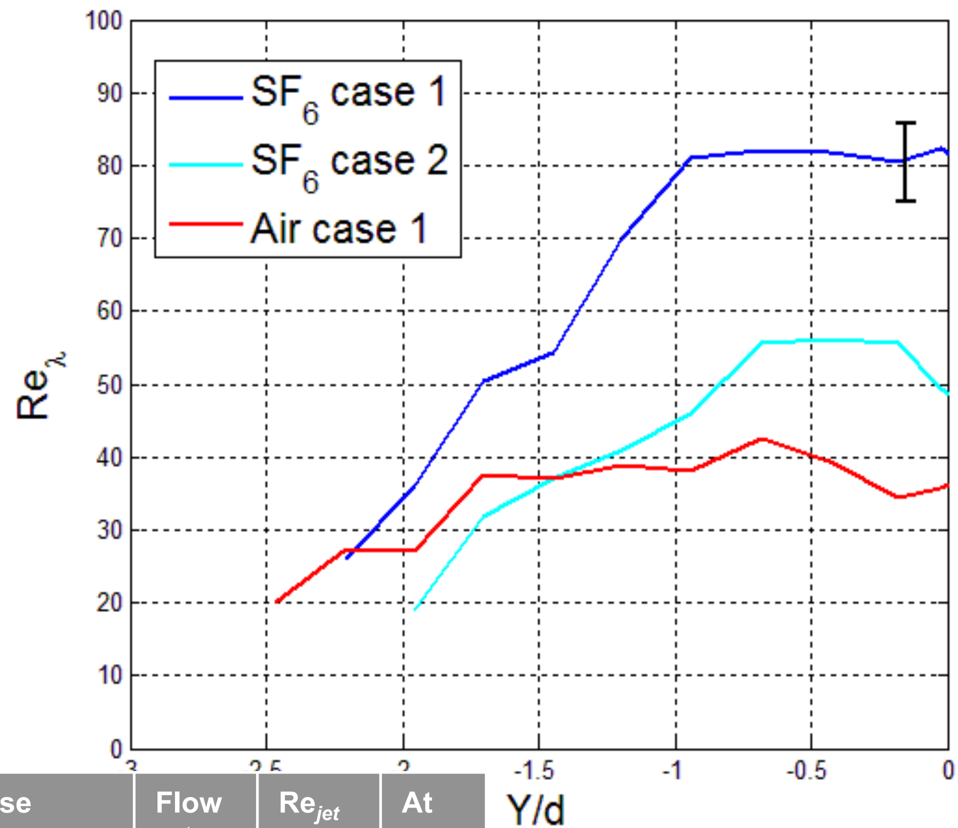
Taylor microscale Reynolds number (calculated across the span of the flow) is higher for high *At* cases

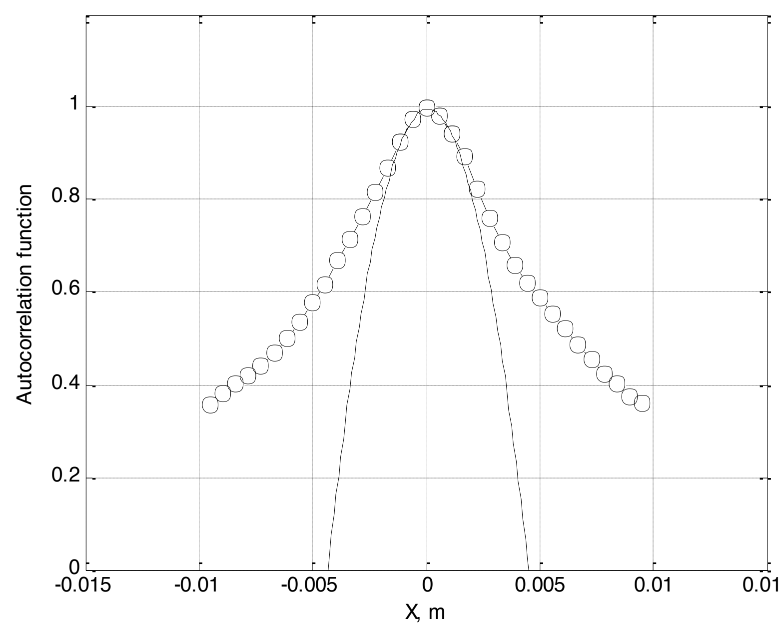
$$Re_\lambda = \frac{\left\langle u'^2_x \right\rangle^{0.5} \lambda}{\nu}$$

Taylor microscale

Local viscosity



Taylor microscale is determined from parabolic fit to velocity autocorrelation function:



$$f(x) = 1 - \frac{x^2}{2\lambda^2} + O(x^4)$$

Case	Flow rate, lpm	Re_{jet}	At
SF_6 case 1	6	6900	0.62
SF_6 case 2	2.5	2600	0.62
Air case 1	6	1600	0.09

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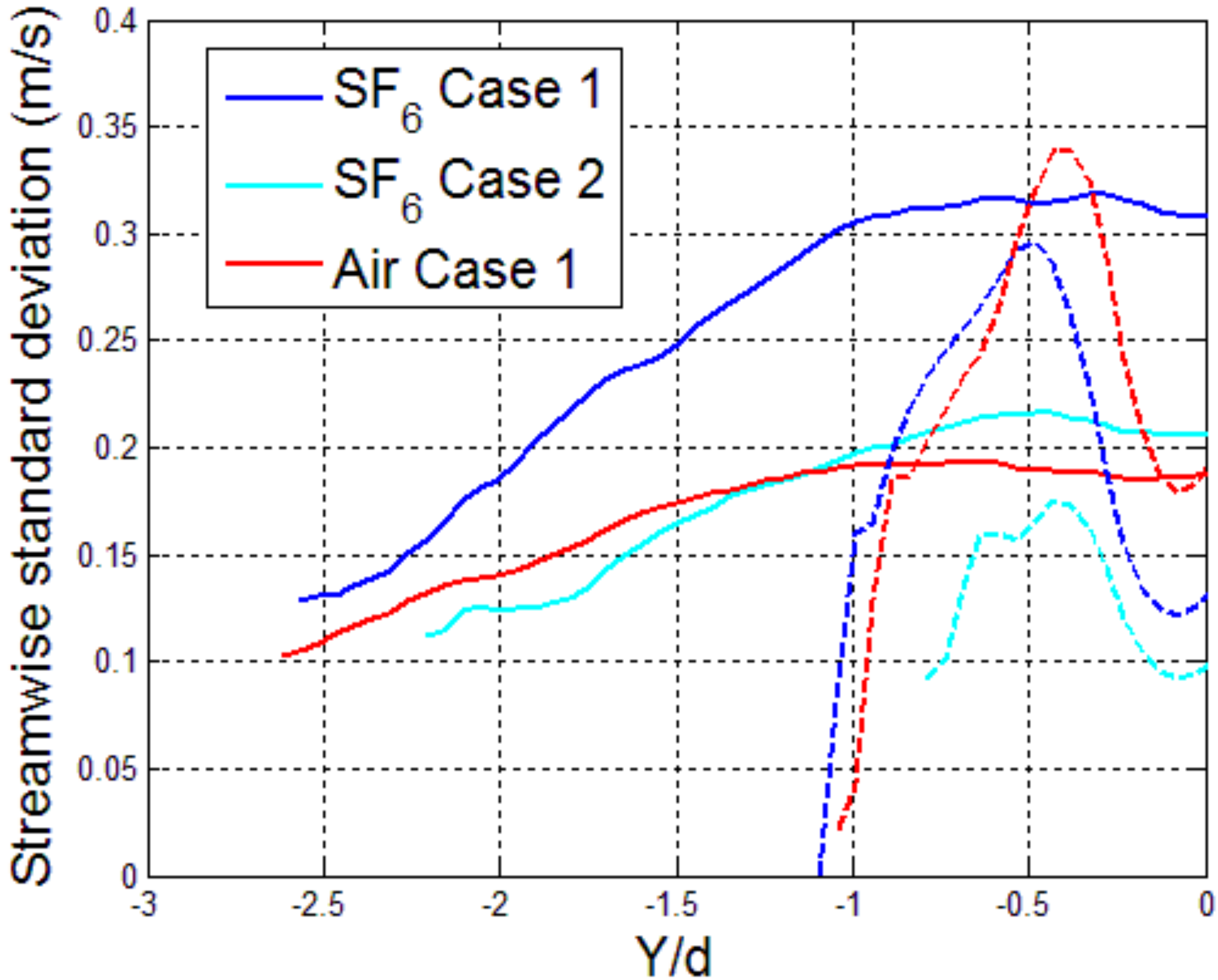
Buoyancy effect: Streamwise velocity standard deviation increases with downstream distance for the SF_6 jets, surpassing the air jet

$$\left\langle u_x' u_x' \right\rangle^{0.5}$$

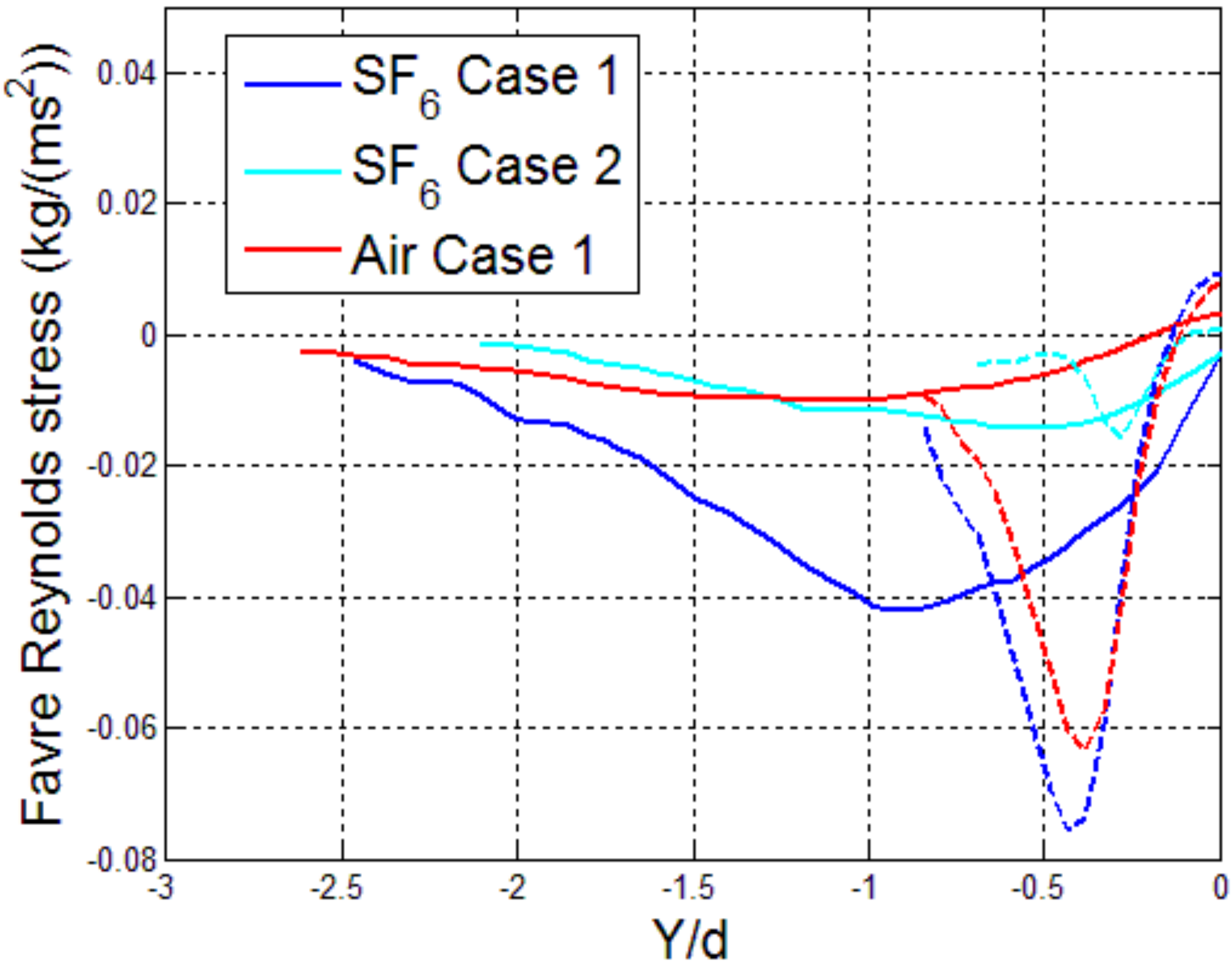


Case	Flow rate, lpm	Re_{jet}	At
SF_6 case 1	6	6900	0.62
SF_6 case 2	2.5	2600	0.62
Air case 1	6	1600	0.09

Buoyancy effect: Reynolds stress follows *At* as we move from momentum- to buoyancy-dominated regime

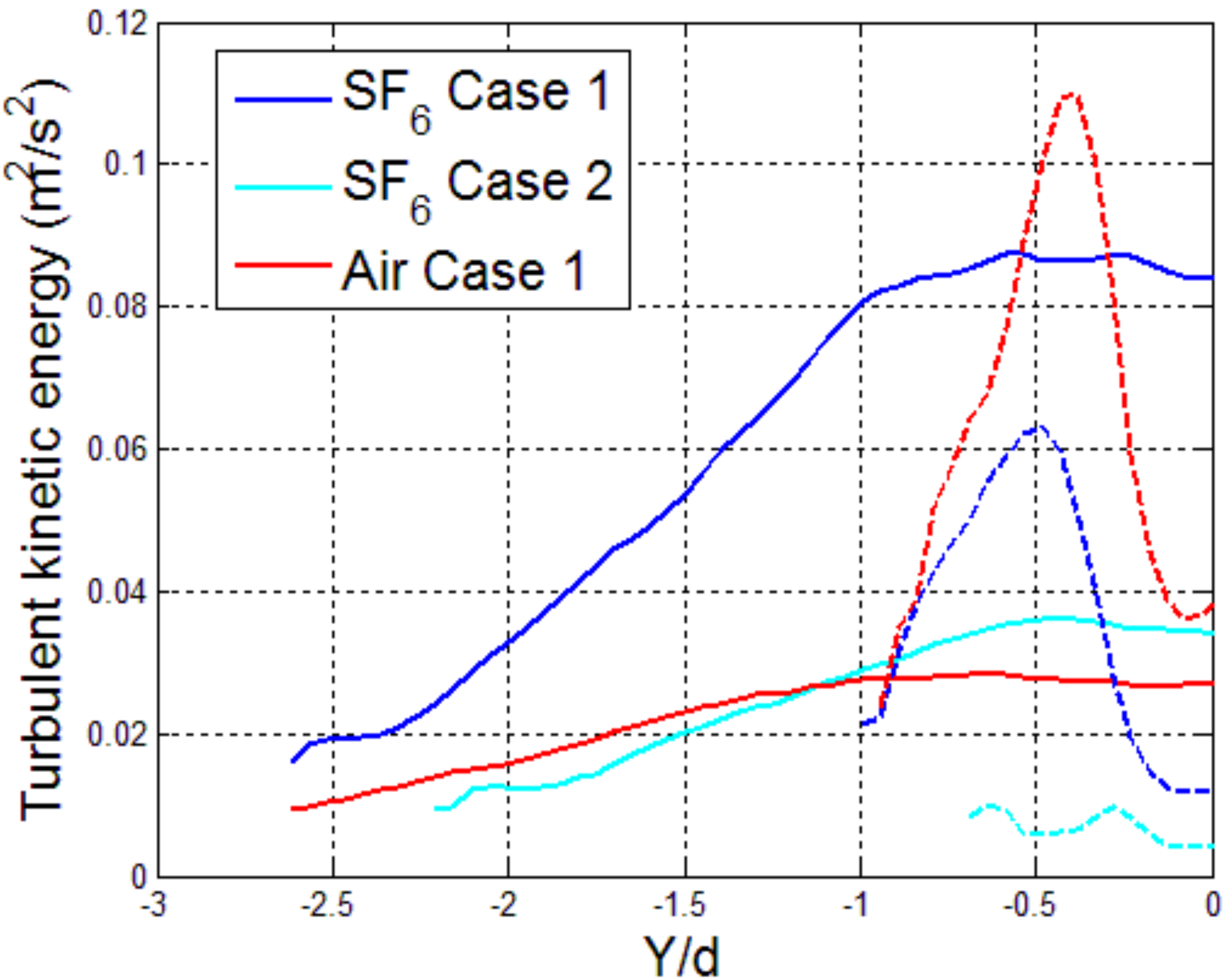
$$R_{xy} = \left\langle \rho \cdot u_x'' \cdot u_y'' \right\rangle$$

$$u_i'' \equiv u_i - \frac{\left\langle \rho \cdot u_i \right\rangle}{\left\langle \rho \right\rangle}$$



Case	Flow rate, lpm	Re_{jet}	At
SF_6 case 1	6	6900	0.62
SF_6 case 2	2.5	2600	0.62
Air case 1	6	1600	0.09

Buoyancy Effect: High At increases TKE away from momentum dominated region



Case	Flow rate, lpm	Re_{jet}	At
SF_6 case 1	6	6900	0.62
SF_6 case 2	2.5	2600	0.62
Air case 1	6	1600	0.09

$$\frac{R_{ii}}{2\cdot\langle\rho\rangle}$$

Experimental work at Los Alamos

VST We are moving our RM diagnostic expertise to the single-interface configuration, specifically targeting initial condition and Ma effects on turbulent mixing that were observed in the gas curtain geometry.

HST Multiphase flow experiments are beginning to characterize unsteady drag forces on shocked particles. Future experiments will study particle size, Ma, and particle evaporation effects.

TMT We have observed buoyancy effects in TKE, Reynolds stress, velocity fluctuations, and other quantities, in a simple Atwood number study using a round jet. Future experiments will carefully parameterize this problem for model development.